ISSN 2395-1621

Fuzzy based prediction of angular distortion of gas metal arc welded structural steel plates

#1M.S.Lohate, #2A.V.Damale

*manojlohate@yahoo.in
#adi_damale@yahoo.com

#1P.G.StudentMechanical Engineering Department SRES College of Engineering Kopargaon
#2Department of Mechanical Engineering SRES College of Engineering Kopargaon

ABSTRACT

Angular Distortion is a major problem and most discussed among the different types of distortion occurring in the welded joints. The main cause of angular distortion is non-uniform transverse shrinkage along the depth of welded plates. The angular distortion restriction may leads to high residual stresses, but can be reduced by providing initial angular distortion in negative direction. So for this the value i:e magnitude of angular distortion must be known. It is difficult to obtain a complete analytical solution to predict the angular distortion.
In this paper the process parameters affecting the angular distortion are studied. The Fuzzy Logic is used for the prediction of angular distortion with the multipass Gas Metal Arc Welding (GMAW) process parameters. The effects of parameters were represented graphically and compared with the experimental results from the references. It was found that the results obtained from Fuzzy logic tool and by experimentation in references, have good agreement between them.

ARTICLE INFO

Article History

Received :18th November 2015

Received in revised form :

19th November 2015

Accepted : 21st November , 2015

Published online :

22nd November 2015

***Keywords*— Angular Distortion,Gas Metal Arc Welding,Fuzzy Logic,Plates,Shrinkage**.

I. INTRODUCTION

A.*Gas Metal Arc Welding* (GMAW)

GMA Automated welding is currently one of the most popular welding methods, especially in a broad range of industrial environments such as deep penetration, smooth bead, low spatter, and high welding speed, areas of renewable energy. In GMA welding processes, due to rapid heating and cooling, the work piece undergoes an uneven expansion and contrast in all the directions heat source is created by an arc and maintained between a consumable electrode wire and work-piece. The weld is formed by melting and solidification of the filler material and base material. Inert gas is allowed to flow during the welding process to shield the weld metals from the surrounding atmosphere. Fig.1.Theschematic representation of the Gas Metal Arc Welding Process.

As product design, to optimize a product, process design is also considerable. The product obtained after process must be at target in terms of value of geometry, size, tolerance etc. and should be acceptable. For this reason, a product which is not affected by uncontrolled parameters must be planned on, in process design. When these expectations mentioned to achieve standard production and continuous challenge are considered, the Importance of automation and automation in manufacturing processes come into existence.

The CO_2 gas shielded metal-arc welding is becoming increasingly popular in the fabrication of boilers,pressure vessels, ship’s hull, etc. The standard has been prepared as a guide to the industry, dealingwith the theoretical and practical aspects of the process.Due to rapid heating and cooling in welding process distortion of welded plates takes place in different directions. Angular distortion is one of the major problems and most pronounced among different types of distortion in the butt welded plates. This angular distortion is mainly due to no uniform transverse shrinkage along the depth of the plates welded. Restriction of this distortion by restraint may lead to higher residual stresses. However, these can be reduced by providing initial angular distortion in the negative direction if the magnitude of angular distortion is known, however it is difficult to obtain a complete analytical solution to predict angular distortion that may be reliable over a wide range of processes, materials, and process control parameters so as to reduce the angular distortion in the welded plates. Prediction of the welding distortion of different materials and the welding joints in reasonable time is essential in the welding industry.

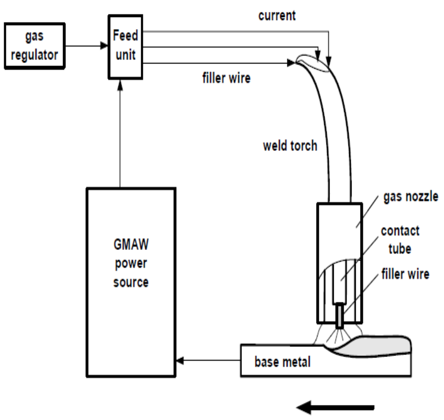


Fig 1Schematic Representation of Gas Metal Arc Welding Process (GMAW)

B. *Welding Process Parameters*

The weld quality depends on a large extent on the bead geometrywhich is largely influenced by various process parameters in theprocess. Inadequacy of weld bead dimensions may lead to failureof the welded structure.As in the welding process rapid heating and cooling is done distortion of welded plate's takes place in different directions. Angular distortion is one of the major problems and most pronounced among different types of distortion in the butt welded plates. The process Parameters which are responsible for the failure of weld or angular distortion are Voltage (V), Travel speed (S) and welding current (I), Wire feed rate (F), Gas Flow rate (G).

*Current*Direct current electrode positive (DCEP) is the most used current in GMAWbecause it gives stable electric arc, low spatter, good weld bead geometry and thegreatest penetration depth. The utilization of relatively low current can give insufficient penetration andexcessive weld reinforcement.

*Voltage*Arc voltage is directly related to current, as indicated above, and with arc length,increasing with it. Voltage also depends on the shielding gas and electrodeextension. The increase of arc voltage widens and flattens the weld bead. Lowvoltages increase the weld reinforcement and excessively high voltages can causearc instability, spatter,and porosity and even undercut

*Welding Speed*Increase in the welding speed gives a decrease in the linear heat input to the work pieceand the filler metal deposition rate per unit of length. The initial increase inwelding speed can cause some increase in penetration depth, because the arc actsmore directly in the parent material, but further increase in speed decreasespenetration and can cause undercut, due to insufficient material to fill the cavityproduced by the arc.

As per the Indian Standards IS 10178 (1995): CO_2 gas shielded metal arc welding ofstructural steels – RecommendationsFirst' Revision the Table Ibelow shows the Typical Welding Conditions For Butt Joints in the Flat Position Automatic welding process.

Fuzzy is a logical system which is an extension of multi valued logic; it is the theory which relates to classes of objects with un-sharp boundaries in which membership is a matter of degree. Fuzzy rule or IF-Then rule plays a central role in all fuzzy logic applications. Calculus of fuzzy rules called fuzzy dependency & command language (FDCL) is effectively one of the principle constituents but not used explicitly in the toolbox. The trend that is growing in visibility relates to the use of fuzzy logic in combination with neuro compacting & genetic algorithm which is the soft computing process. Unlike the traditional and hard computing, soft computing process accommodates the imprecision of the real world. Soft computing plays an important role in the conception & design of the systems whose machine IQ is much higher than that of the system designed by the conventional method. Fuzzy logic is all about the relative importance of precision, how important is it to be exactly correct when a rough answer will do. Fuzzy logic is anemerging area of research because it does a good job of trading off between significance & precession. Fuzzy is something that humans have been managing for a very long time.

Fuzzy logic is the convenient way for mapping of input space to the output space which is starting point of everything. Loti Zadeh who is said to be the father of Fuzzy logic states or said that; in almost every case you build the same product without fuzzy logic, but fuzzy is tool which is faster and cheaper.

Fuzzy Logic is the simple to understand, the Mathematical concept which is used for the fuzzy reasoning is very simple. Fuzzy logic is a more intuitive approach without the reaching far complexity. It is flexible as, with any given system or systems it is easier to layer on more functionality without starting again from scratch. Fuzzy logic is said to be tolerant of imprecise data and also it is very powerful tool for dealing quickly and efficiently with imprecision and nonlinearity.

*Why Fuzzy Logic*Now a day the trend is growing towards the soft computing instead of hard computing so as to reduce the cost of manufacturing .Fuzzy logic is a tool which is available in MATLAB toolbox. As stated in the previous study in the reference papers, Fuzzy is a logical system which is an extension of multi valued logic. Fuzzy rule or IF-Then rule plays a central role in all fuzzy logic applications. Fuzzy logic is all about the relative importance of precision, how important is it to be exactly correct when a rough answer will do. Fuzzy logic is a useful area of research because it does a good job of trading off between significance & precession. Fuzzy is something that humans have been managing for a

Material Thickness	Wire Diameter	Welding current	Arc Voltage	Wire Feed Rate	Welding Speed	No. of Passes	Joint Preparation	Root Face	Root Gap	Remark
mm	mm	A	V	mm/min	mm/min			mm	mm	
1	1	105	20	3250	1300	1	SCB	-	-	-
2	1	135	20	4500	800	1	SEOB	-	0.8	-
3	1	165	22	5900	650	1	SEOB	-	1.5	-
6	1.6	350	32	5300	360	1	*SCB	-	-	--
10	1.6	350	32	5300	200	2	SCB	-	-	-
					180	2	*SSV-30^0	-	1.5	-
20	1.6	430	34	6300	150	2	DSV-30^0	6	-	HCT
35	2.0	700	42	5600	100	4	DSV-50^0	6	-	HCT
					120					
50	2.0	750	46	6000	80	6	DSU-10^0	10	-	HCT
					150			RR-6		

SBC-Square close butt SSV-Single side V *Backing Strip

SEOB-Square edge open butt DSV-Double side V HCT-High current technique

DSU-Double side U RR-Root radius

computing process. Unlike the traditional and hard computing, soft computing process accommodates the imprecision of the real world. Soft computing plays an important role in the conception & design of the systems whose machine IQ is much higher than that of the system designed by the conventional method. Fuzzy logic is all about the relative importance of precision, how important is it to be exactly correct when a rough answer will do. Fuzzy logic is anemerging area of research because it does a good job of trading off between significance & precession. Fuzzy is something that humans have been managing for a very long time.

Fuzzy logic is the convenient way for mapping of input space to the output space which is starting point of everything. Loti Zadeh who is said to be the father of Fuzzy logic states or said that; in almost every case you build the same product without fuzzy logic, but fuzzy is tool which is faster and cheaper.

Fuzzy Logic is the simple to understand, the Mathematical concept which is used for the fuzzy reasoning is very simple. Fuzzy logic is a more intuitive approach without the reaching far complexity. It is flexible as, with any given system or systems it is easier to layer on more functionality without starting again from scratch. Fuzzy logic is said to be tolerant of imprecise data and also it is very powerful tool for dealing quickly and efficiently with imprecision and nonlinearity.

*Why Fuzzy Logic*Now a day the trend is growing towards the soft computing instead of hard computing so as to reduce the cost of manufacturing .Fuzzy logic is a tool which is available in MATLAB toolbox. As stated in the previous study in the reference papers, Fuzzy is a logical system which is an extension of multi valued logic. Fuzzy rule or IF-Then rule plays a central role in all fuzzy logic applications. Fuzzy logic is all about the relative importance of precision, how important is it to be exactly correct when a rough answer will do. Fuzzy logic is a useful area of research because it does a good job of trading off between significance & precession. Fuzzy is something that humans have been managing for a very long time and also it is faster and cheaper. Fuzzy logic is simple to understand and is flexible to use also it is very powerful tool for dealing quickly and efficiently with imprecision and nonlinearity.

D. *Applications of Fuzzy Logic*

Fuzzy Logic is a soft computing method which is very simple and flexible so it is been used in wide range of applications as, Coal Power Plant, Water Treatment Systems,

AC Induction Motor, Fraud Detection, Customer Targeting, Quality Control, Nuclear Fusion, Truck Speed Limiter, Toasters, Photocopiers, Vacuum Cleaners, Credit

II.LITERATURE REVIEW

A number of researchers have tried theoretically or experimentally the ways to predict the welding distortions and welding residual stresses. Some of them have also tried to predict the thermal and mechanical responses of welding structure in practice industrial production.

Two dimensional non linear transient welding simulations with three dimensional structural analyses in a decoupled approach. Using two dimensional thermo mechanical welding process simulations for determining the temperature loading for a three dimensional structural model determine buckling distortion after welding in large and complex structures. The simplified FEM to simulate out of plane distortion caused by fusion butt welding; he replaced the thermal transient process to a simple two dimensional treatment and thermo elastic plastic process to a simple analytical algorithm. The welding distortion and residual stresses of a thin plate panel structure using FEA based on the inherent shrinkage method.

Wang Rui et.al[4] have made the prediction of welding distortion in bead on plate welding and fillet welding with Stainless steel using the three dimensional thermo elastic plastic finite element method using an in –house finite element code of iterative substructure method .In addition to this he has also conducted the experiments to validate the predicted result.

Dongcheol Kim and Sehun Rhee[5] has state that stability of the welding parameters as welding arc is essential to get the good quality weld in CO_2 welding process. Weld quality is dependent on arc stability and minimizing the effects of disturbances or changes in the operating condition commonly occurring during the welding process. In order to minimize these effects, a controller can be used. Fuzzy controller was used in order to stabilize the arc during CO_2 welding. The control rules of the fuzzy controller were formed using the authors' experience and knowledge of the welding process. The control parameters to be tuned were the membership functions. Therefore, the controller's performance depended on the membership functions. The Taguchi parameter design, which makes the control performance insensitive to the operating condition changes and noise, was used to determine the membership functions. He found smaller the mita index value the more stable the arc became, the welding voltage which minimized the Mita index should be determined to find the welding voltage value online, which maintained the stable arc state or minimized the Mita index, the fuzzy controller was used. The L_9 (3^4) orthogonal array wasused in Fuzzy Logic tool box to validate the results obtained by the Taguchi method for the stabilization of arc in CO_2 welding process. The fuzzy controller with the obtained optimal control parameter settings showed a

satisfactory control performance under different welding conditions.M. Vural et.al [3]examine the effect of welding fixture used to prevent the distortions during cooling process utilizing a robot controlled gas metal arc welding

method on cooling rate and distortions of welded structures. He tested six different types of AISI 1020 steel specimens using the specially designed welding fixture for the welded steel structure in three different welding speeds and two different cooling conditions either at fixture or without using fixture. Also he states that designed fixture is reduced amount of distortions. The preheating effect of previous weld on the next weld has increased distortions on the other side of part. Increase in distortions is directly proportional to the increase in welding speed which affects the weld heat input.

V. Murugan et.al[1]studied the effects of the process parameters on the angular distortion, he states that 'α' decreases with the increase in't' where 'α' is angular distortion and't' is time between the successive passes.The angular distortion is more when t is shorter, because more bead width provides more contraction in the top of the bead. When t is longer, a larger amount of heat is lost by the plate and the temperature is lower compared to when t is shorter, so the amount of angular distortion is less.The angular distortion α increases with the increase in N. Generally, in an unrestrained joint, the degree of angular distortion is approximately proportional to the number of passes. The slope of the curve decreases with the increase in N. In multipass welds, previously deposited weld metal provides restraint, so the angular distortion per pass decreases as the weld is built up.

Similarly the angular distortion a decreases with the increase in wire feed rate F.As the wire feed rate increases the welding speed has also to be increased to maintain the volume of material in the v groove of welded plates.

III .PROBLEM DEFINITION

As per the survey of the work done in this area, we are on a stage of defining the problem which we are going to consider in this project. Problem definition is a final statement in which we are framing a scope of work to be carried out in specific way and also defining steps to be executed in a structured way. The problem definition is given along with the flow chart of steps to be performed during project work.

Angular distortion is one of the most pronounced and major problems among different types of distortion in the butt welded plates.This angular distortion is mainly due to no uniform transverse shrinkage along the depth of the plates welded. Restriction of this distortion by restraint may lead to higher residual stresses. However, these can be reduced by providing initial angular distortion in the negative direction if the magnitude of angular distortion is predictable. As stated by the Kim and Rhee it is difficult to find or predict or obtain the exact analytical solution for the angular distortion, to optimize the GMAW process and to make it a cost-effective one by eliminating the weld defects due to angular distortion.The main work is to study the process parameters responsible for the angular distortion and to predict the angular distortion in GMAW welded structural steel plates by Fuzzy Logic tool from MATLAB R2009a software and to verify the results by experimental analysis.

The Fig.2 Flow chart below shows the steps to be carried out during the project work.

IV.FUZZY LOGIC TESTING

The fuzzy Study is done using the data taken from the literature[1].

A. *Getting Started*

Structural steel plate (IS: 2062) specimens 300x150x25 mm were welded together. The edge preparation and welding sequence for different number of passes is shown in Fig. 3

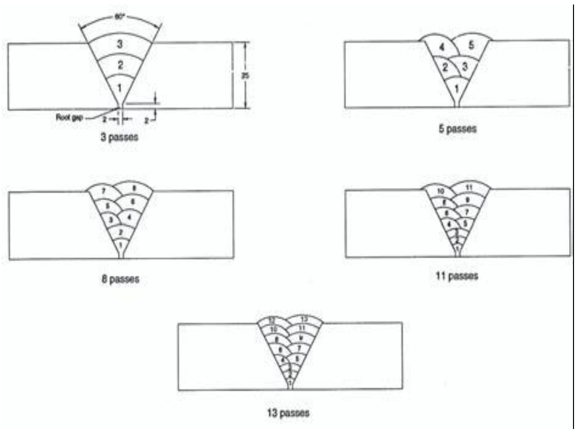


Fig3 Cross section of the weldment for different number of passes [1]

The angular distortion (α) is to be measured using sine bar principle with the help of a vernier height gauge. It requires a Dial Gauge, Sine Bar. Slip Gauges, Vernier Height Gauge Dial Gauge Stand and Surface Plate. The measurement of the plate is done before the welding process and the readings are recorded and again the readings are taken after the welding process is done by considering the designed values of the process parameters. The algebraic summation of the reading before and after the welding process is done which sows the difference in the reading; this difference is nothing but the deformation in the welded plate which is angular distortion. A plate with distortion is shown in Fig.4.

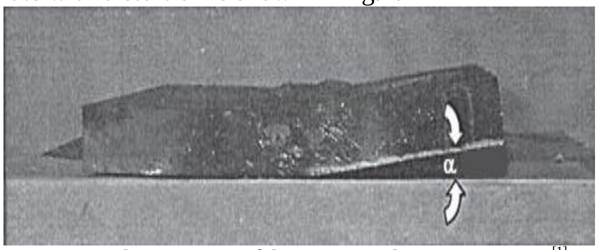


Fig 4Angular Distortion of the Specimen during Experiment [1]

B. *Parameters and Limits*

As the main of the project is to study the process parameters and predict the angular distortion in the GMAW process by fuzzy logic, the readings recorded for the angular distortion whose limits were as shown in the Table II below.

Considering the limits of the process parameters as defined above in the Table II the results obtained by the experimental testing done by [1] were recorded and displayed as shown in the Table III.The Table III shows the Design matrix and the observed values of angular distortion.

TABLE III
DESIGN MATRIX AND OBSERVED VALUES OF ANGULAR DISTORTION[1]

Sr.No	T	N	F	α(Degree)
1	-1	-1	-1	6.37
2	+1	-1	-1	6.23
3	-1	+1	-1	8.92
4	+1	+1	-1	8.45
5	-1	-1	+1	5.80
6	+1	-1	+1	5.68
7	-1	+1	+1	8.40
8	+1	+1	+1	7.59
9	-1.682	0	0	7.82
10	+1.682	0	0	7.24
11	0	-1.682	0	5.91
12	0	+1.682	0	9.50
13	0	0	-1.682	8.05

14	0	0	+1.682	6.89
15	0	0	0	7.76
16	0	0	0	7.70
17	0	0	0	7.59
18	0	0	0	7.53
19	0	0	0	7.70
20	0	0	0	7.12

As discussed in the previous topic the experimental results were obtained and the response of the same is recorded in the tabulated format in Table III which shows the designed matrix and the angular distortion for the respective matrix formed.

The Dongcheol Kim and Sehun Rhee has used orthogonal array $L_9(3^4)$ in fuzzy logic tool box for controlling the arc stability in GMAW process. And he found that the results obtained were near about to the experimental results recorded, and also we can get the values of the outputs by varying the inputs parameters so as to know the optimum values of the process parameters.

C. *Steps in Fuzzy Logic*

Step-1

At the start of the fuzzy we have to prepare the range for the output angular distortion by considering the process parameters form the results recorded by the experimentation and categorized in the three steps Low, Medium and High, The Table IV shows the outputs i:e angular distortion range as high medium and low.

TABLE IV
RANGE OF THE OUTPUT FOR FORMATION OF RULES IN FUZZY LOGIC

Categories	Range (α degree)
Low	5.68 to 7.12
Medium	7.24 to 7.7
High	7.76 to 9.5

Step-2

Considering the above given ranges of the output angular distortion form the results recorded by the experimentation the rules were formed by using the orthogonal array and the results recorded as in Table III.The rules formed in the fuzzy logic toolbox are as shown in Fig 5.

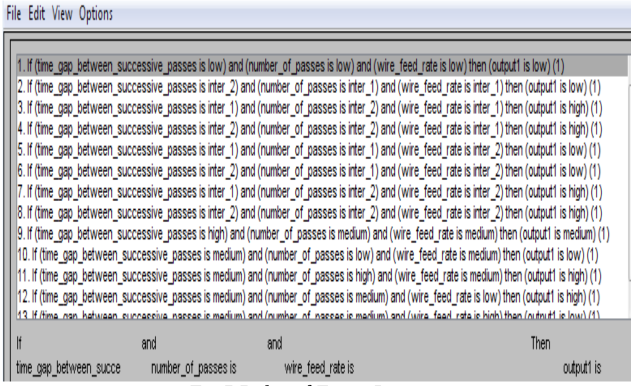


Fig.5 Rules of Fuzzy Logic

Step-3

After the preparation of the rules in the fuzzy logic tool box these rules are viewed which shows the graphical representation of the rules developed as shown in the Fig 6 below. At the same time we can put the input values of all the input parameters and we get the output parameter values. The values obtained by the fuzzy toolbox are near about to the experimental value. We can also slide the red line so as to change the parameters and we get the output values of the same.

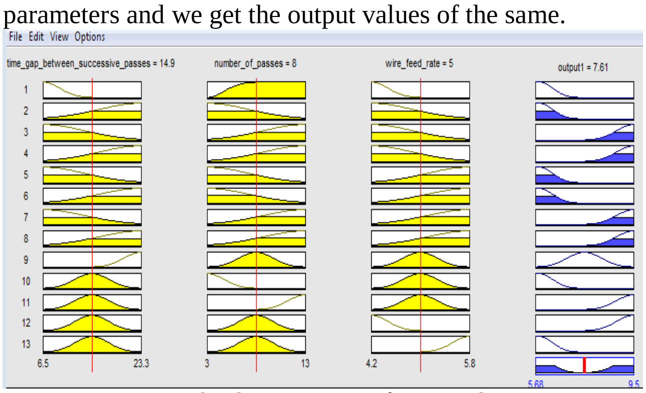


Fig.6 Graphical representation of Fuzzy Rules

Step-4

As per the fuzzy logic rules developed in the previous steps the toolbox shows the relation between the process parameters graphically which states the effects of the process parameters on the angular distortion of the GMAW welded structural steel plates. The Fig.7 below represents graphically the relation between the input and output parameters.

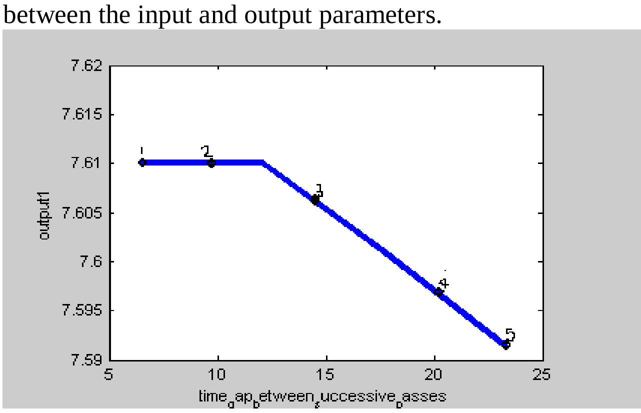


Fig7 Relationbetween Time Gap and Angular Distortion

The graph clearly shows that as the Time gap between the successive passes is less the angular deformation in the GMAW plates is at higher rate and as the Time gap between the successive passes is increased the angular distortion goes on reducing. This means the Time between the successive passes and the angular distortion are inversely proportional to each other up to some extend and the angular distortion after a limit remains constant though the time gap is increased.

Similarly the other parameter which is Number of passes the relation with angular distortion is shown in Fig 8

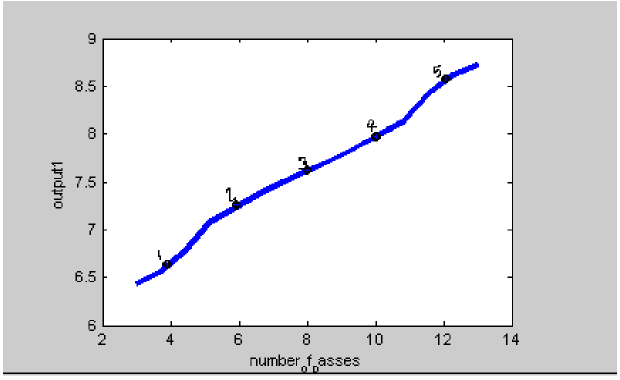


Fig.8 Relation between Number of Passes and Angular Distortion

The graphical representation between the number of passes and the angular distortion shows that as the number of passes is less the angular distortion is less as the no of passes are increases i: e in the medium range the angular distortion is increases and as the no of passes increases more than the medium range the angular distortion also increases.

As well the third parameter which is wire feed rate, the graph shown in the Fig.9 shows the relation between the wire feed rate and the angular distortion which shows as the wire feed rate goes on increasing the angular distortion goes on decreasing.

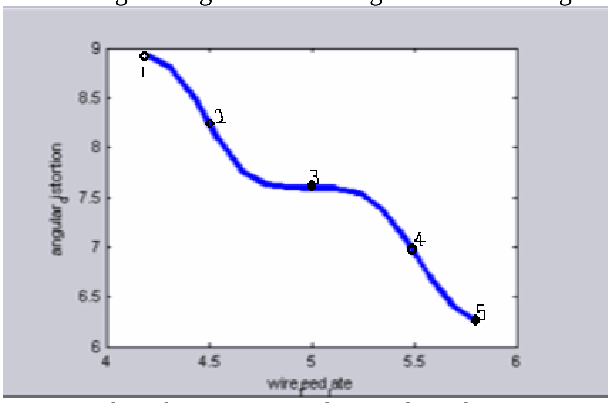
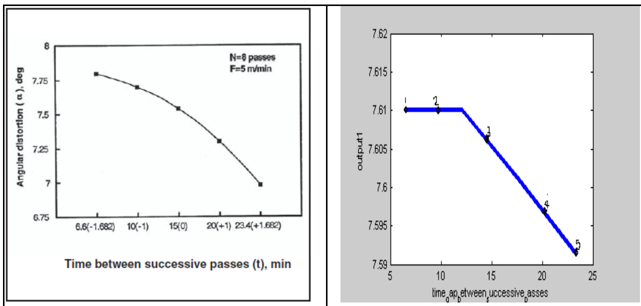


Fig.9 Relation between Wire Feed Rate and Angular Distortion

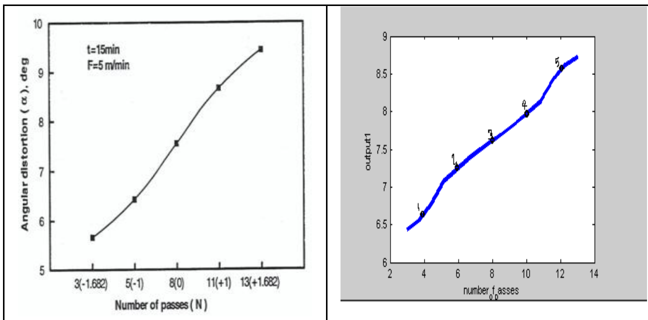
V.COMPARISON OF RESULTS

In the previous chapters we have studied the effects of the various process parameters on the angular distortion of the GMAW structural steel plates here the graphs plotted by the mathematical and experimental process and the graphs shown by the fuzzy logic toolbox are shown below which gives the clear idea about the effect of process parameters on the angular distortion of welded plates.



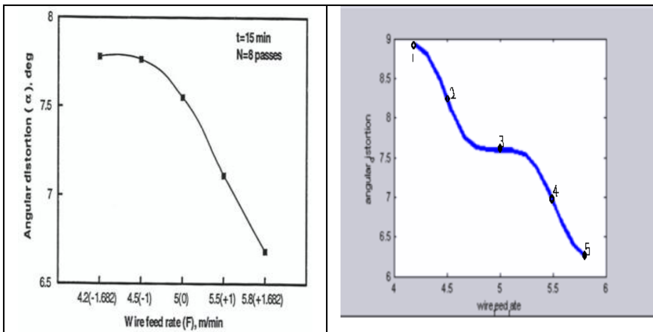
Reference Fuzzy

Fig.10 Comparison Effect of Time Gap on Angular Distortion



Reference Fuzzy

Fig. 11 Comparison of Effect of Number of passes on Angular Distortion



Reference Fuzzy

Fig 12 Comparison of Effect of Wire Feed Rate on Angular Distortion by Experimental and Fuzzy Logic.

The results obtained by the Fuzzy logic toolbox in Matlab software is the validated with the reading from the literature review and then it is found that the results are nearly somewhat close to the reference values as that obtained by the Authors in previous study The Comparison of the Values by Fuzzy Logic and the experimental values from the literature review is tabularized below.

TABLE V
COMPARISON OF VALUES OF ANGULAR DISTORTION AND VALUES PREDICTED BY FUZZY LOGIC

Sr. No	T	N	F	α (Degree)	α(Degree) By Fuzzy Logic	% Variation
1	-1	-1	-1	6.37	6.68	4.751
2	+1	-1	-1	6.23	6.30	1.1173
3	-1	+1	-1	8.92	9.03	1.2256
4	+1	+1	-1	8.45	8.93	5.523
5	-1	-1	+1	5.80	5.68	2.09
6	+1	-1	+1	5.68	5.88	3.4602
7	-1	+1	+1	8.40	8.25	1.8018
8	+1	+1	+1	7.59	7.57	0.2639
9	-1.682	0	0	7.82	7.75	0.8992
10	+1.682	0	0	7.24	7.3	0.8253
11	0	-1.682	0	5.91	6.08	2.8357
12	0	+1.682	0	9.50	8.38	12.528
13	0	0	-1.682	8.05	7.99	0.7481
14	0	0	+1.682	6.89	7.08	2.720
15	0	0	0	7.76	7.59	2.215
16	0	0	0	7.70	7.59	1.4388
17	0	0	0	7.59	7.59	0
18	0	0	0	7.53	7.59	0.7937
19	0	0	0	7.70	7.59	1.4388
20	0	0	0	7.12	7.59	6.3902

The table above clearly shows that the values of angular distortion obtained by the fuzzy logic somewhat nearer to the earlier predicted values of angular distortion.

VI. CONCLUSION

The conclusions below were arrived at from this investigation. The Fuzzy logic tool can be used for predicting the angular distortion of multipass welds. As per the results outcome by fuzzy logic and comparing it with the reference output, out of the three process variables selected for investigation, the number of passes (N) had a strong effect on angular distortion (α). The value of α is about 9.03deg when other parameters are at lower limits, and it is about 5.88 deg when other parameters are at higher levels. The increasing trend of the angular distortion with the increase in number of passes has to be considered carefully in practice to control angular distortion. The process parameters, namely, time between successive passes (t) and wire feed rate (f), have a negative effect on angular distortion.

ACKNOWLEDGEMENT

Any work always accomplishes by help and support of many people. So I would like acknowledge all such people here.

I would like to extend my deepest gratitude towards my guide Dr. A. V. Damale, Mechanical Engineering Department, SRES College of Engineering, Kopargaon. I would like acknowledge his help by pushing me forward in the work in correct direction.

The people who had helped me directly or indirectly, I am highly thankful to all of them and I apologies that their names are cover here.

I am very much thankful to my family members for their patience and consistent support to me from all respects.

REFERENCES

1. V. VelMurugan And V. Gunaraj,"Effects of Process Parameters on Angular Distortion of Gas Metal Arc Welded Structural Steel Plates" Supplement to the *Welding Journal*, November 2005pp 165-s – 171 s.
2. MohdShaharSulaiman, Yupiter HP Manurung1, EsaHaruman, Mohammad Ridzwan Abdul Rahim, MohdRidhwanRedza, Robert NgendangAk. Lidam, SunhajiKiyai Abas, GhalibTham and Chan Yin Chau "Simulation And Experimental Study On Distortion Of Butt And T-Joints Using WELD PLANNER" Journal Of Mechanical Science And Technology 2011,pp.2641~2646.
3. M. Vural, H.F. Muzafferoglu, U.C. Tapici "The effect of welding fixtures on welding distortions"Journal of Achievements in Materials and Manufacturing Engineering,vol-20,2007,pp 511- 514.
4. Wang Rui, RashedSherif, SerizwaHisashi, Murakawa and Zhang "Numerical And Experimental Investigationon Welding Deformation" Transaction of JWRI, Vol.37, 2008, pp 79-90.
5. Dongcheol Kim and Sehun Rhee "Design of a Robust Fuzzy Controller for the Arc Stability of CO_2 Welding

Process Using the Taguchi Method" IEEE Transactions, Vol-32,2002, pp-157-162.

6. Adinath.V.Damale and Keshav.N.Nandurkar,Numerical Simulation of Side Heating for Controlling Distortion in MMAW Butt Welded Plates,SADHANA (*A Springer Journal*):DOI:10.1007/s12046-014-0322-x.Vol.40,No.2,April.2015,pp 487-502
7. Dr. K.Lalit Narayan, Ch. Ramakrishna, Dr. M.M.M. Sarcar, Dr. K.Mallikarjuna Rao "Optimization of CO_2 Welding Process Parameters for Weld Bead Penetration of SS41 Mild Steel Using Response Surface Methodology" IJRMET Vol-4, 2014, pp-27-30.
8. Indian Standard CO_2Gas Shielded Metal-Arc Welding Of Structural Steels-Recommendations –IS 10178:1995, pp 1-9.
9. J Edwin, Raja Dhas&SomasundaramKumanan "Weld Residual Stress Prediction Using Artificial Neural Network And Fuzzy Logic Modelling" Indian Journal Of Engineering Material Science, Vol-18, 2011, pp-351-360.
10. Timothy J. Ross, "Fuzzy Logic With Engineering Applications" A John Wiley and Sons, Ltd., Publication, Third Edition, 2010,pp-48-145.
11. Lotfi A. Zadeh "Fuzzy Logic Toolbox or Use With Matlab" 1995 - 2002 By The Mathworks

