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Research Article

Effect of Various Parameters on Angular Distortion in Welding

Ajay Kumar*

Mechanical Engineering Department, Deen Bandhu Chhotu Ram University of Science and Technology, Murthal. Sonipat, India

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Abstract

Angular distortion is a major problem and most pronounced among different types of distortion in the butt welded plates. This angular distortion is mainly caused by the non-uniform extension and contraction through thickness direction due to the temperature gradient. Restriction of this distortion by restraints may lead to higher residual stresses. However, if the magnitude of the angular distortion is predictable, these can be reduced by providing initial angular distortion in the negative direction. 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. Presently, several analytical methods and empirical formulas have been developed to give quantitative information. In this study, the statistical method of three factors, two level full factorial designs has been used to develop mathematical model to correlate angular distortion in metal inert gas. The distortion is found to be significantly influenced by no of passes, time gap between successive passes and joint gap. Direct and interaction effects of the process parameters are also analyzed and presented in the graphical form.

Keywords: *Welding, Distortion, Statistical design.*

1. Introduction

As a fabrication technology, welding presents a number of technical challenges to the designer, manufacturer, and end-user of the welded structures. While welding joins the components of a structure together, the complex thermal cycles from welding result in formation of residual stresses in the joint region, and distortion of the welded structure. Both weld residual stress and distortion can significantly impair the performance and reliability of the welded structures. They must be properly dealt with during design, fabrication, and in-service use of the welded structures. Distortion in a weld results from the expansion and contraction of the weld metal and adjacent base metal during the heating and cooling cycle of the welding process. Doing all welding on one side of a part will cause much more distortion than if the welds are alternated from one side to the other. During this heating and cooling cycle, many factors affect shrinkage of the metal and lead to distortion, such as physical and mechanical properties that change as heat is applied.

If a metal is uniformly heated and cooled, there would be almost no distortion. However, because the material is locally heated and restrained by the surrounding cold metal, stresses are generated higher than the material yield stress causing permanent distortion. The principal factors affecting the type and degree of distortion are:

- Parent material properties
- Amount of restraint
- Joint design
- Edge preparation and Part fit-up
- Welding procedure

1.1 Prediction of angular distortion

Watanable and Satoh reported a relationship for angular distortion which is described as:

$$\delta = C_1\left(\frac{I}{h\sqrt{vh}}\right)^{m+1} \exp\left\{-C_2\left(\frac{I}{h\sqrt{vh}}\right)\right\}$$

Where

δ = Angular distortion

C_1 is directly proportional to $\left(\frac{\eta V}{\phi^{0.25}}\right)^{2.5}$

C_2 is directly proportional to $\left(\frac{\eta V}{\phi^{2..25}}\right)$

m is a constant = 1.5

η = Heat efficiency of welding arc

ϕ = Diameter of the electrode

V = Arc voltage

v = Welding speed

h = Thickness of the plate

I = Welding current

*Corresponding author: Ajay Kumar is working as Assistant Professor

Artem Pilipenko reported another relationship for angular distortion which is described as:

$$\delta = 0.13\frac{IV}{vh^2}$$

Where,
V = Arc voltage
v = Welding speed
h = Thickness of the plate
I = Welding current

1.2 Process Parameters affecting angular distortion

The process input parameters which affect the angular distortion in welding are:

- No of layers on the weld
- Welding speed
- Welding current
- Arc voltage
- Large size electrode
- Joint gap
- Wire feed rate
- Electrode stick out
- Rate of cooling
- Time gap between successive passes.
- Quality of the parent material and electrode.

Here we are considering three factors which have negative significant effect on distortion; these are no of passes, joint gap and time between successive passes.
These three parameters are called Control parameters and the remaining parameters are kept constant, so these are called Constant parameters.

2. Literature

There have been many significant and exciting developments to analyze and control distortion in the past ten to fifteen years. The progresses in the last decade have not only greatly expanded our fundamental understanding of the processes and mechanisms of residual stress and distortion during welding, but also have provided powerful tools to quantitatively determine the detailed distortion information for a given welded structure.
Murgan and Gunaraj (2005) developed a statistical method of three factors, five levels factorial central composite rotatable design to develop mathematical model to correlate Angular distortion with multiple pass Gas Metal Arc Welding process parameters. Process control parameters like Time gap between successive passes, Number of passes and Wire feed rate were analyzed to find out their effect on angular distortion. This mathematical model helped to optimize the GMAW process and to make it a cost effective one by eliminating the weld defects due to Angular distortion. Michaleris and Debiccari (1997), presented a numerical analysis technique for predicting welding induced distortion. The technique combined two dimensional welding simulations with three dimensional structural analyses in a decoupled approach. The numerical technique was particularized on evaluating welding induced buckling. The utilization of 2-D analysis is for the welding simulation reduced the computational time and cost. Decoupling the weld simulation from the 3-D analyses permitted these analyses to be performed elastically, which allowed for them to be solved quickly and efficiently. Puchaicela (1998) reviewed and analyzed several formulas and figures to provide welding engineers and fabricators with a practical guide for the control and reduction of distortion. In this qualitative analysis of the corresponding empirical formulas, the effect of different welding and fabrication parameters on the magnitude is discussed
Onnaji *et al* (2004), proposed the optimization the weld sequence of a sub-assembly composed of thin walled aluminum alloy extruded beam structure using a 2D beam element model. Here the main factor considered was the quality of the assembly after welding. Two distortion modes (angular shrinkage and tilting shrinkage) were investigated and applied to model welding distortion. A composite quality index was formulated, which is a weighted measure of critical deformation and overall deformation. For simulating welding deformation and role of sequence, some weld sequence were selected heuristically and were simulated in ANSYS 5.2. Based on quality index of theses sequence, some were reproduced while mutating other portion of these sequences to find better sequences. Fucuda and Yoshikawa (1990), applied a neural network method for the welding sequencing problem of a simple butt-welded construction. But, their major concern was to minimize the movement of a welding torch. They did consider sequencing to minimize welding distortion, but only for a very simple construction with inherent symmetry in the structure Huang *et al* (1997) proposed genetic algorithms for sequencing type problems and applied their genetic algorithm to test problems, including a spot welding task sequencing problem. They implemented the algorithm to decide the weld sequence of a simple structure in which welding points were approximately linearly distributed. However they did not consider characteristics of arc welding operation.

3. Design of Experiment

The honor of discovering the idea of design of experiment belongs to Sir Ronald Fisher. Box and Wilson in their paper proposed that an investigator organizes consecutive small no of trials, in each of which all the factors are simultaneously varied according to definite rules. The series are so organized that after mathematical processing of preceding ones it will be possible to further select the conditions for conducting the experiment that is to design the experiment.

The design of experiment is the procedure of selecting the number of trials conditions for running them, essential and sufficient for solving the problem that has been set with the required precision.

The purpose of the theory of design experiment is to ensure that the experimenter obtains data relevant to his hypothesis in as economical a way as possible following a sequential way of analysis. Fisher has summed up the advantage of factorial experiments in that they result in:

1. Greater efficiency
2. Greater comprehensiveness in that:
   (a) Effects of factors are estimated
   (b) Conclusions drawn from factorial experiments have wider inductive basis.

Conventional methods of experiment with multiple parameter and responses are time consuming, costly and even inadequate for the prediction of the distortion. Design of experiments using half factorial design is used so that several parameters response can be simultaneously studied.

3.1 Factorial Design

In industrial applications frequently we know that several factors may affect the characteristics in which we are interested and wish to estimate the effects of each of the factors and how the effect of one factor varies over the levels of the other factors.

For example, quality of the weld joints may be affected by types of electrode used, current, voltage and gap etc. We are often tempted to test each of the factors separately holding all other factors constant in a given experiment but with a little thought it might be clear that such an experiment might not give the information required. The logical procedure would be to vary all factors simultaneously within the framework of the same experiment.

3.2 Selection of Design

Investigation in the effect of welding parameters on weld distortion being one of the major part of investigation, it was considered best to design experiments for the phase of study, which included the effect of maximum no of parameters and hence could be used for all other phases of investigation.

The distortion in welding is affected by no of passes, joint gap, time b/w successive passes, welding current, welding speed, arc voltage, plate thickness, electrode stick out and electrode size.

Here it is decided to take 3 parameters in to account. Thus the no of parameters are three and result in 2^3 =8 trials or combination of experimental conditions. The eight trials as selected and all the three parameters are to be analyzed simultaneously by confounding the main effects with two factor interactions.

3.3 Selection of the two levels of the welding parameters

For conducting the actual experiments it is necessary to find out the working zone for combination of parameters, which ensures high quality beads from the point of view of appearance, lack of defects like macro cracking; non-uniform ripples on the bead, excessive convexity and spatter, surface porosity, geometrical inconsistency etc. On the basis of preliminary experiments conducted using the no of passes, time b/w successive passes and joint gap were kept between 4-8, 10-20min and 2-4mm respectively.

3.4 Development of a Design matrix

The design matrix developed to conduct the eight trials of full factorial design. For the sake of simplicity the parameters form X_1 to X_3 are represented only by the subscripts 1 to 3. The signs under the column 1,2,3 are arranged in standard Yate's order.

Table1: Welding Parameters and their Limits

Parameters	**Symbols**	**Units**	**Limits**	
			Low(-1)	**High(+1)**
No of passes	N	-	4	8
Time b/w successive Passes.	T	Min	10	20
Joint gap	G	Mm	2	4

Table 2 Design matrix of welding parameters

S.no	N	T	G	Distortion
	1	2	3	
1	-	-	-	6.12^0
2	-	-	+	7.45^0
3	-	+	-	7.27^0
4	-	+	+	6.73^0
5	+	-	-	7.66^0
6	+	-	+	8.43^0
7	+	+	_	6.89^0
8	+	+	+	8.04^0

3.5 Selection of Mathematical Model

To predict the distortion response, a mathematical model is to be developed after conducting the experiments. The no of independent variables in the design matrix are three and dependent variable is angular distortion that is also called response function or response factor.

The response function of interest, (Angular distortion), can be expressed as:

$$D= f (N, T, G) \quad (a)$$

Assuming linear relation and considering the two factor interactions, response factor can be expressed as

$$D= b_0 + b_1 X_1 + b_2. X_2 + b_3.X_3 + b_{12}.X_1.X_2 + b_{13} .X_1.X_3 + b_{23} X_2.X_3 \quad (b)$$

Where b_0, b1, b2, b3, b12, b13, b23andare coefficients.
Where 'D' is the angular distortion parameter. Assuming a linear relationship in the first instance and taking in to account all the possible two factor interactions and it could be written as:

$D=b_0+b_1N+b_2T+b_3G+b_{12}TG+b_{13}NG+b_{23}T$ (c)

3.8 Evaluation of the coefficients

The regression coefficients of the selected model are calculated using equation given below. This is based on method of Taguchi design with MINITAB SOFTWARE 15.

Where,

Smaller is better
$(s/n) = -10\log(MSD_{LB})$

Where MSD = 1/R€(Y^2)
R = no of repetitions.
MSD=Mean Square deviation

3.9 Development of model

Model was developed by the method of regression. Adequacy of the model and significance of coefficients was tested by the analysis of variance technique and student's 't' test respectively. By finding the regression coefficients we get the mathematical model.

$$D = b_0 + b_1N + b_2T + b_3G + b_{12}TG + b_{13}NG + b_{23}NT$$

4. Experimental Procedure

The experiments were conducted on mild steel plates of size 100 x 75 x 20 mm plate as par the design matrix (Table 2). A 30^o V- grove was made on each plate so as to make butt joint. Each one of the cleaned plate was welded employing an electrode positive polarity. Weld beads were deposited in the V- groove using mild steel wire. The plates were cleaned chemically and mechanically to remove oxide layer and any other source of hydrogen, before welding. Weld bead were deposited using a mechanized Metal inert gas (MIG) machine to ensure the reproducibility of the data. This also eliminated the effects of welder's skill on the result.

The complete sets of eight trials were repeated once to determine the 'variance of optimization parameters' for the model. The experiments were performed in a random order to avoid any systematic error. The work limits of the parameters are selected as shown in table 1 and2.

5. Results and Discussion

As shown in figure 1, the angular distortion increases from 6.92^0 to 7.7^0 with the increase in No of passes (N) from 4 to 8. This shows direct effect of number of passes on angular distortion(D). From this, it is clear that the D increases with increase in N. In multi pass welds, previously deposited weld metal provides restraints, so the angular distortion per pass decreases as the weld is built up.

It can observed be from the figure 2 that angular distortion increases from7.00^0 to 7.62^0 with the increase in joint gap from 2 mm to 4 mm. It is due to the fact that for a sound welding joint, as the joint gap increases, the number of passes has to be increased which results in more amount of metal deposited in the V-groove. As the no of passes increases the heat input per unit length increases. Due to this increased heat input, the distortion increases.

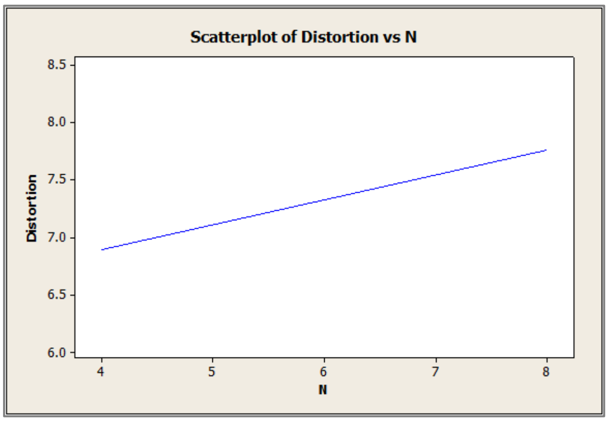

Figure 1: Effect of no of passes (N) on Angular distortion

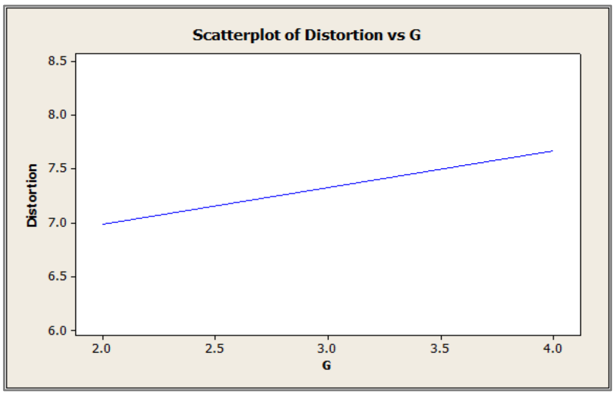

Figure 2: Effect of Joint gap (G) on Angular distortion

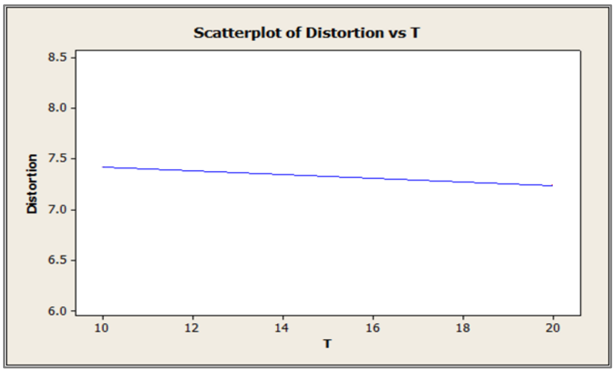

Figure 3: Effect of time b/w passes (T) on Angular distortion

It can observed be from the figure 3 that angular distortion decreases from7.450 to 7.320 with the increase in time gap from 10 min to 20 min. It is clear that D decreases with increase in T. When T is longer more heat is lost by the plate and the plate temperature is lower as compared to that when T is less. So some of the heat applied to the plate during the next pass will be utilize in pre heating the plate. Hence the net heat added to the plate is less compared to when the plate temperature is high.

When t is longer, a large amount of heat is lost by the plate and the temperature is lower compared to when T is shorter. So, the heat applied to the plate during the next pass will result in a marginal rise in temperature of the plate, and hence, D is less.

From the figure 4 it is clear that when N is 4 the value of distortion is increases from 6.79^0 to 6.92^0 and when the value of no of passes is 8 then the value of angular distortion D decreases from 8.12^0 to 4.41^0. Therefore it is clear from the figure that this interaction has negative effect on the angular distortion D.

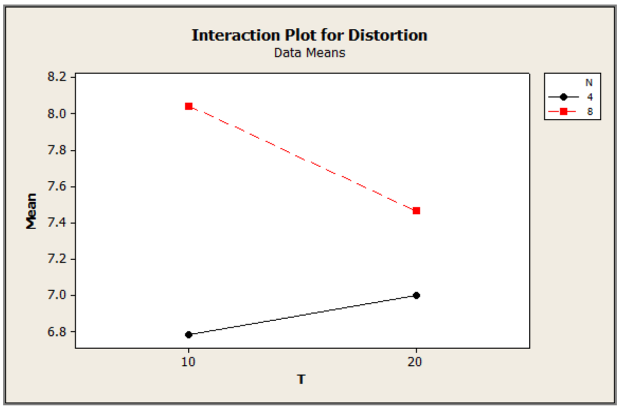

Figure 4: Interaction effect of No of passes and time gap on Angular distortion.

From figure 5 it is clear that when the time gap is 10min b/w successive passes then the angular distortion is increases from 6.88^0 to 7.95^0 and when the value of T is 20min then the value of angular distortion is 7.12^0 to 7.36^0. It is due to the fact when T is longer more heat is lost by the plate and the plate temperature is lower as compared to that when T is less. So some of the heat applied to the plate during the next pass will be utilize in pre heating the plate. Hence the net heat added to the plate is less compared to when the plate temperature is high.

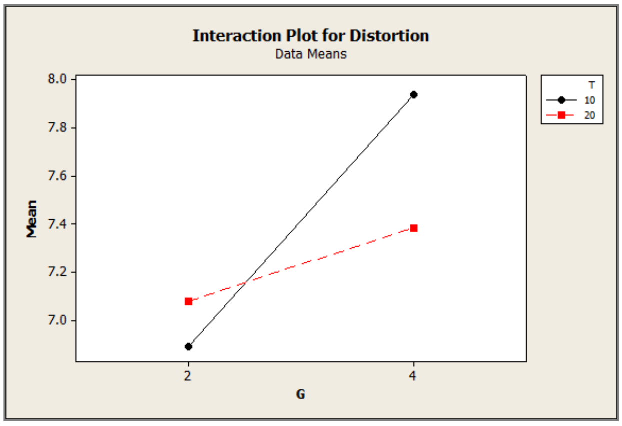

Figure 5: Interaction effect of time between successive passes & joint gap

From the figure 6 it is clear that when the value of joint gap is 2mm then with the increase in no of passes from4 to 8 the value of angular distortion increases from 6.70^0 to 7.23^0.and when the value of joint gap is 4mm then with the increases in no of passes from 4 to 8 the value of angular distortion increases from 7.13^0 to 8.25^0.

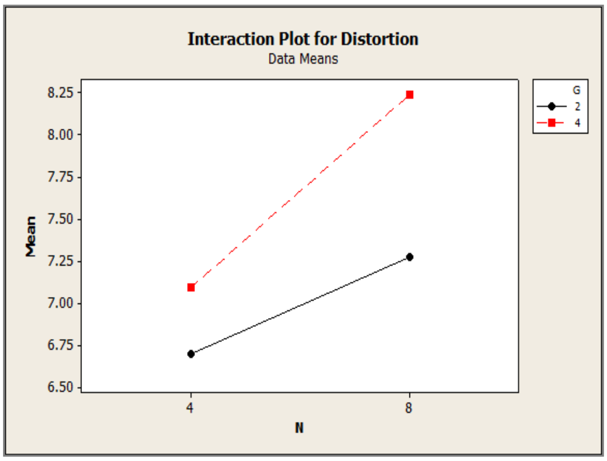

Figure 6: Interaction effect of Joint gap and No of passes on Angular distortion.

Conclusions

The following conclusions were arrived at from the above investigation:

1. The full fraction factorial design can be employed easily for developing mathematical model for optimizing the distortion within the workable region of the control parameters like no of passes, joint gap, and time gap between successive passes in Metal inert gas welding.
2. Angular distortion increases with the increase in number of passes within the design range of parameters.
3. With the increase in joint gap, the angular distortion increases within the design range of parameters.
4. Angular distortion decreases with the increase in time gap between successive passes within the design range of parameters.
5. The process parameters like no of passes and joint gap have positive effect on angular distortion.
6. The process parameter Time between successive passes has negative effect on angular distortion.
7. Within the design range of parameters, the highest effect on angular distortion is found of number of passes.
8. Within the design range of parameters, the least effect on angular distortion is found time between successive passes.
9. The angular distortion is minimum when the number of passes is 4, joint gap is 2 mm and time between successive passes is 20.
10. The optimum value of angular distortion is 6.64^0.

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