EFFECT OF PROCESS VARIABLES ON ANGULAR DISTORTION OF PULSE MIG WELDED HSLA PLATES

by

A. MANDAL* and R.S. PARMAR**

Prod. Engg. Dept., NIFFT, Hatia, Ranchi, Bihar

** Mech. Engg. Dept., I.I.T. Delhi, New Delhi

ABSTRACT

Angular distortion is a major problem and most pronounced amongst different types of distortion in the butt welded plates. It is difficult to obtain a completely analytical solution to the problem of angular distortion which may be reliable over a wide range of processes, materials and procedural variables. In this study, the statistical method of 2 level full factorial technique has been used to develop models which correlate angular distortion with Pulse MIG process variables and joint parameters.

INTRODUCTION

Although fusion welding processes are extensively used in industries for fabrication, a number of disadvantages are associated with them. One of the major problems associated with any fusion welding process is the distortion of the workpiece produced due to the development of residual stresses in the weldment as a consequence of localised non-uniform heating and cooling of the joint area. The magnitude of distortion, or even whether it will take place or not, will depend upon the following factors (1) :

1. The magnitude of the welding stresses developed
2. The nature of distribution of these stresses in the weldment
3. The strength of the members upon which these stresses act

Also, the level of distortion depends on a number of factors such as :

1. *Process parameters (2-5)* - welding process used, welding current, arc voltage, heat input, welding speed, size of electrodes, etc.
2. *Material properties* - composition of the parts to be joined, thermal and physical properties of the materials to be joined (4,6), as well as electrodes and fluxes used for the purpose.
3. *Welding procedure* - joint configuration like root gap (7,8), number of passes (5,9), sequence of welding (10,11) and nature of restraints (12), cross-section area of the joint groove (3,13), etc.

The magnitude of the problem increases with the complexity of the structure to be fabricated.

Angular distortion is a major problem and most pronounced of the different types of distortion in the butt welded plates. Angular distortion occurs in a butt weld when transverse shrinkage is not uniform throughout the thickness of the plate, which is mostly the case when medium thick plates are welded from one side using multipass welding.

It is difficult to obtain a completely analytical solution to the problem of angular distortion which may be reliable over a wide range of processes, materials and procedural variables. The most common approach for studying angular distortion is empirical, or a combination of empirical and analytical methods (3,5).

PLAN OF INVESTIGATION

To study the effect of welding variables on the angular distortion, the investigations were planned to be carried out in the following steps:

i. Identification of the independent welding and joint design variables affecting the angular distortion

ii. Determining the useful limits of these variables

iii. Development of the design matrix to conduct the experiments in a systematic fashion

iv. Conducting the experiments as per the design matrix

v. Development of mathematical models based on regression

vi. Evaluating the coefficients and checking the adequacy of the models

vii. Analysis of results and conclusions

To study the effects of shielding gases on angular distortion, the experiments were carried out **in two phases** depending on the shielding gases used.

A. With Industrially Pure Argon as Shielding Gas

Identifying the Process Variables

The pulse current parameters are shown in **Fig.1** for identification. It was found that process parameters like peak current (I_p), mean current (I_m), welding speed (W) and butt joint angle (A) had profound effect on bead geometry and angular distortion. It was, therefore, decided to use these four process parameters to determine their effects on angular distortion of butt joints. Welding quality Argon was selected for use as the shielding gas. Microalloyed steels of 10 mm and 16 mm thicknesses were selected for use in the investigation as these thicknesses are extensively employed in the fabrication industries.

Selection of the Useful Limits of Process Variables

The useful limits of the four process variables were determined by conducting a large number of preliminary experiments. The qualifying criteria for welding parameters were based on the following factors:

i. Stable arc with spray mode of metal transfer

ii. Spatter-free welding

iii. Defect-free welds based on visual inspection

iv. Maximum filler wire feed rate possible without disturbing any of the above conditions

Based on these considerations the limits of different variables were arrived at

Developing the Design Matrix

It was decided to employ statistical techniques, not only from the economic viewpoint, but also because it was possible to arrive at an equation which would correlate pulse and other parameters of pulse MIG welding process to angular distortion of V-butt welded plates.

It is reported by Arya and Parmar (14) that no curvature effects have been statistically significant, over the ranges of various factors studied, affecting angular distortion in V-butt welded plates. So it was decided to use two-level full factorial designs to study the effects of various factors on the angular distortion.

For simplifying the recording of the conditions of the experiments and the subsequent analysis, the two levels i.e. the upper level and lower level of the factors were

$$Im = \frac{Ip * Tp + Ib * Tb}{T}$$

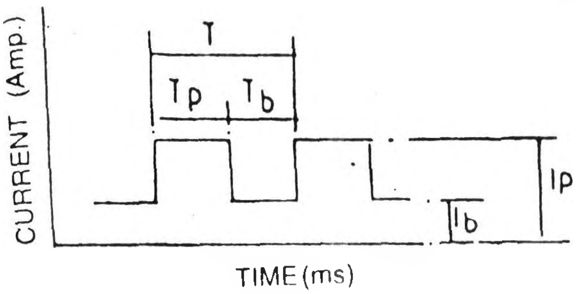
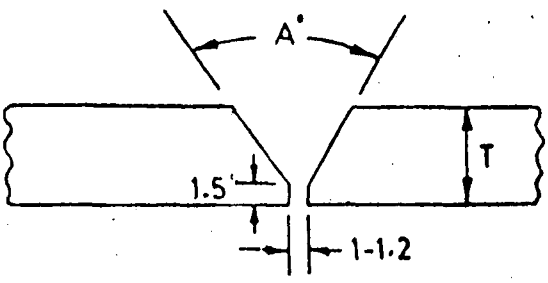


Fig. 1 : Pulse Current Parameters

TABLE I - The Design Factors, their Symbols and Values			
FACTOR	SYMBOL	LEVELS (+1)	(-1)
Mean Current	I_m (amp)	200	160
Peak Current	I_p (amp)	350	300
Welding Speed	W (cm/min)	35	20
Joint Angle	A (degree)	90	45



Where A – Joint Angle
T – Thickness of Plates

Fig. 2 : Joint Configuration Used

codified as +1 and -1 respectively, with the help of the formula given below :

$$X_c = \frac{2^* (X - X_{max})}{X_{max} - X_{min}} + 1$$

where

X_c = the coded value of the factor

X = any value of the factor between X_{max} and X_{min}

X_{max} = maximum (natural) value of the factor

X_{min} = Minimum (natural) value of the factor.

The factors, their levels and actual values together with the pulse and process parameters are tabulated in **Tables I** and **II**. The design matrix in coded form is given in **Table III** and is based on the method by Davis (15).

Experimental Procedure

Specimens of size 250 mm x 150 mm were machined from HSLA (TISTEN 60 supplied by TISCO, India) steel plates. The joint specifications used are given in **Fig. 2**. In order to maintain a root gap between 1 to 1.2 mm, two tack welds, one at each end, were made after placing a neatly cut 1 mm thick sheet in between the plates. The thin sheet was immediately removed after tack welding. A flat asbestos sheet was placed over the table of welding manipulator. The plates to be welded were placed over the asbestos sheet to avoid any burn through and damage to the manipulator table. Tab-in and tab-out were used for each run. NPD (nozzle to plate distance) was kept fixed at 27 mm for all cases, to take the advantage of high feed rate of filler wire.

For studying the effect of thickness of the plates on angular distortion, two sets of experiments were carried out on plates

TABLE II - Pulse and Process Parameters used for Welding

Sl. No.	I_p amp	I_m amp	T_p msec	I_b amps	T_b msec	Wire Feed Rate m/min
1	350	200	4.9	56	5.1	7.2
2	350	160	5.3	20	7.2	6.0
3	300	200	5.9	56	4.1	6.6
4	300	160	6.3	18	6.2	5.7

TABLE III - Design Matrix				
Sl. No.	I_p	I_m	W	A
1	1	1	1	1
2	-1	1	1	1
3	1	-1	1	1
4	-1	-1	1	1
5	1	1	-1	1
6	-1	1	-1	1
7	1	-1	-1	1
8	-1	-1	-1	1
9	1	1	1	-1
10	-1	1	1	-1
11	1	-1	1	-1
12	-1	-1	1	-1
13	1	1	-1	-1
14.	-1	1	-1	-1
15	1	-1	-1	-1
16	-1	-1	-1	-1

of two different thicknesses i.e. 10 mm and 16 mm.

The joints were welded according to the design matrix but in a random fashion, to eliminate the possibility of systematic error creeping in the result. For all cases of Argon shielding root run was laid with lowest possible heat input. The root run was laid using highest welding speed i.e. 35 cm/min, to minimise heat input. The pulse and process specifications of root run are given at Sl. No. 4 of **Table II**. Sealing runs were laid for 16 mm thick plates only. The distortion of the welded plates were measured before and after the sealing runs using Vernier Height Gauge. The set-up used for measurement of distortion is shown in **Fig. 3.**

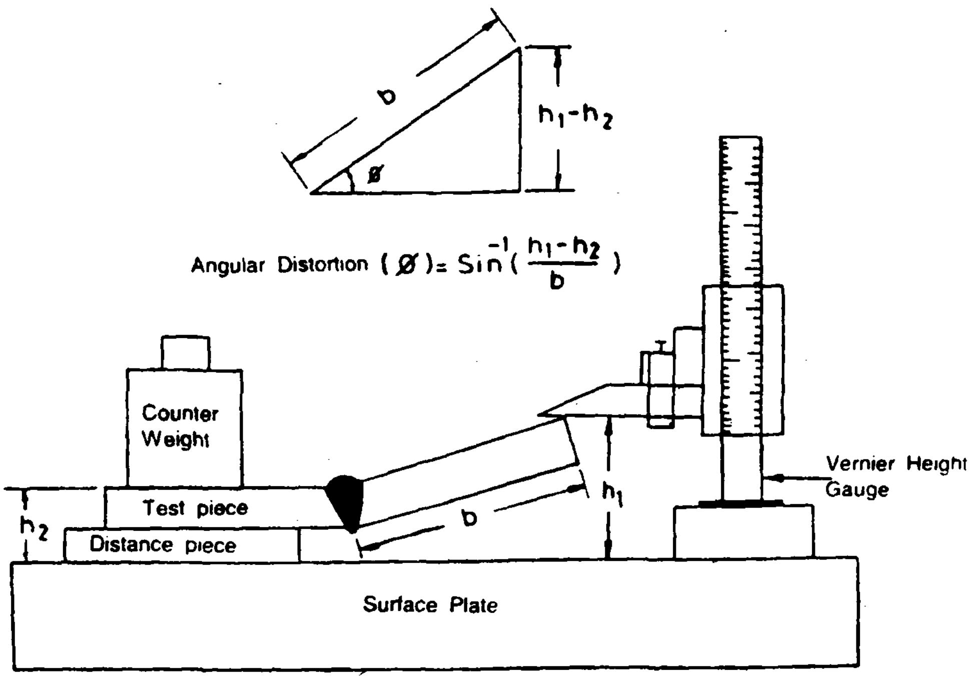


Fig. 3 : Arrangement for Measurement of Angular Distortion

Development of Mathematical Models

The polynomial chosen for representing the relationship between angular distortion and the factors, is given below :

ANGULAR DISTORTION (Deg) = $B_0 + B_1 I_p + B_2 I_m + B_3 W + B_4 A + B_5 I_p{*}I_m + B_6 I_p{*}W + B_7 I_p{*}A + B_8 I_m{*}W + B_9 I_m{*}A + B_{10} W{*}A + B_{11} I_p{*}I_m{*}W + B_{12} I_p{*}W{*}A + B_{13} I_p{*}I_m{*}A + B_{14} I_m{*}W{*}A + B_{15} I_p{*}I_m{*}W{*}A$

where B's represent the coefficients of the model.

Evaluating the coefficients and checking the adequacy of the models.

The measured values of angular distortion are given in **Table IV**. Since each trial had a different weld metal deposition rate per unit length, the number of runs required to complete the joints was not the same. Number of runs used for different treatment combinations are listed in **Table IV**. These measured angular distortion values were used to calculate the coefficients of the models, and the adequacy of the models was checked by calculating the F-ratio as per Adler (16). As the above design could not give an independent estimate of the error, in the absence of replicates, it was assumed that 3rd and higher order interactions were not significant. These interactions were summed up to give the error of the experiments (16) with five degrees of freedom. The significance of each term was checked by carrying out students' t-test. Final models containing the significant terms only are given below :

a. Thick Plates Before Sealing Run

Angular Distortion (degree) = $6.13252 + 0.4247{*}I_m + 0.7407{*}W + 1.2524{*}A + 0.4568{*}W{*}A$

b. Thick Plates After Sealing Run

Angular Distortion (degree) = $5.51937 + 0.193{*}I_p + 0.388{*}I_m + 0.8094{*}W + 1.298{*}A + 0.4556{*}W{*}A$

TABLE IV – Observed Angular Distortion (degree) and number of Welding passes used to fill up the joints

Design Matrix Number	Angular Distortion (degree)			No. of Passes	
	16 mm Plates (before sealing run)	16 mm Plates (after sealing run)	10 mm Plates	16 mm Plates	10 mm Plates
1	9.3	8.7	7.711	13	5
2	8.59	8.1	7.519	13	5
3	8.09	7.65	7.23	13	5
4	7.88	8.35	6.66	13	5
5	7.29	6.45	5.35	6	3
6	6.54	5.74	4.20	6	3
7	5.62	5.15	4.128	6	3
8	5.3	4.87	3.7	7	3
9	5.96	5.5	5.93	6	3
10	5.24	4.57	5.6	6	3
11	4.836	4.33	5.2	6	3
12	4.62	3.9	5.643	6	4
13	4.92	4.45	4.85	3	3
14	4.618	3.75	3.57	3	3
15	4.22	3.47	2.91	3	3
16	4.627	3.8	3.53	3	3

c. Thin Plates

Angular Distortion (degree) = $5.233 + 0.358^{*}I_m + 1.203^{*}W + 0.579^{*}A + 0.2643^{*}W^{*}A$

B. With Ar-CO_2 Mixture as Shielding Gas

To study the effect of shielding gas and welding sequence on the extent of angular distortion, quite a few joints were produced by varying I_m, W, A, thickness of plates and shielding gas composition. The welding conditions along with measured values of angular distortion are given in **Table V**. For all the joints considered, the pulse parameters and process variables for the root run are given in Sl. No. 12 of **Table V**. The joint specifications and welding procedure were same as given above under Phase A except when specifically mentioned.

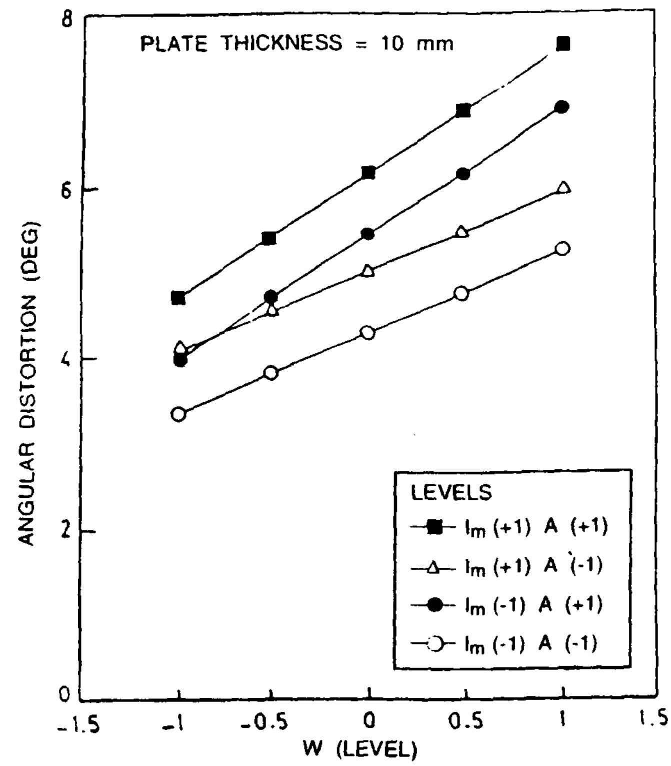


Fig. 4 : Effect of Welding Speed on Angular Distortion

TABLE V – Welding Parameters and Distortion Values for process using Ar-CO_2 Shielding Gas

Sl. No.	I_p amp	I_m amp	T_p msec	I_b amp	T_b msec	W cm/min	A degree	Wire feed rate m/min	Shielding Gas	Thickness mm	Passes root+no. of passes	Measured values of distortion degree
1	300	200	4	100	4	20	45	7.1	Ar+5%CO_2	10	2	3.48
2	350	200	3	77	3.7	20	45	7.7	Ar+5%CO_2	10	2	3.7
3	300	200	5.5	78	4.5	20	45	7.6	Ar+5%CO_2	10	2	3.53
4	350	200	4	100	6	20	45	7.6	Ar+5%CO_2	10	2	3.43
5	350	200	4	50	4	20	45	8.2	Ar+5%CO_2	10	2	3.64
6	300	200	5.5	78	4.5	20	45	7.6	Ar+15%CO_2	10	2	3.58
7	300	200	5.5	78	4.5	20	45	7.6	Ar+25%CO_2	10	2	3.68
8	300	200	5.5	78	4.5	35	45	7.6	Ar+5%CO_2	16	4	3.65
9	350	200	4	50	4	35	45	8.2	Ar+5%CO_2	16	4	3.69
10	300	200	5.5	78	4.5	35	45	7.6	Ar+15%CO_2	16	4	3.78
11	300	200	5.5	78	4.5	35	45	7.6	Ar+25%CO_2	16	4	3.75
(Root run) 12	300	160	4	31	4.3			5.7				

ANALYSIS OF RESULTS

Analysis of results for 10 mm and 16 mm thick plates **with industrially pure Argon as shielding gas** is as follows :

10 mm Thick Plates

For easy interpretation of the effects of various pulse and process parameters, a number of graphs have been drawn based on the models developed above.

Fig. 4 shows the interaction effect of welding speed (W), joint angle (A) and I_m on angular distortion. Irrespective of the levels of I_m and joint angle, distortion increased with welding speed. Theoretically, angular distortion should decrease as welding speed increases, as the heat input per unit length of the joint decreases. But as welding speed increases, number of passes required to fill up the joint also increases. So total heat input per unit length of the joint increases, hence angular distortion also increases. As joint angle increased, more weld metal was used to fill up the joint, hence more distortion was observed.

It may also be observed that as I_m (mean current) increased, the angular distortion also increased. This can be explained on the basis that as current increases, heat input also increases and hence that results in increase in angular distortion.

16 mm Thick Plates

Figs. 5 and 6 show the interaction effect between I_n, welding speed and groove angle on one hand and angular distortion on the other for welding of 16 mm thick plates. The influences of I_m, W and A on angular distortion are similar to those for 10 mm thick plates; however, the magnitude of angular distortion is higher for 16 mm thick plates when all other operating variables are same. This is due to the increased amount of filler metal required to fill up the joints in 16 mm thick plates as compared to joints in 10 mm thick plates. Comparing **Fig. 5** with **Fig. 6** it is observed that the angular distortion had decreased slightly with the sealing run.

As sealing run was, obviously, laid opposite to the joint face, the plates bent in the opposite direction as the weld metal cooled, leading to reduction of distortion. The magnitude of the angular distortion for all the cases studied was quite high. It can be seen that within each group, based on same thickness and joint angle, no significant variation on the angular distortion has taken place due to change in I_p and pulse frequency levels.

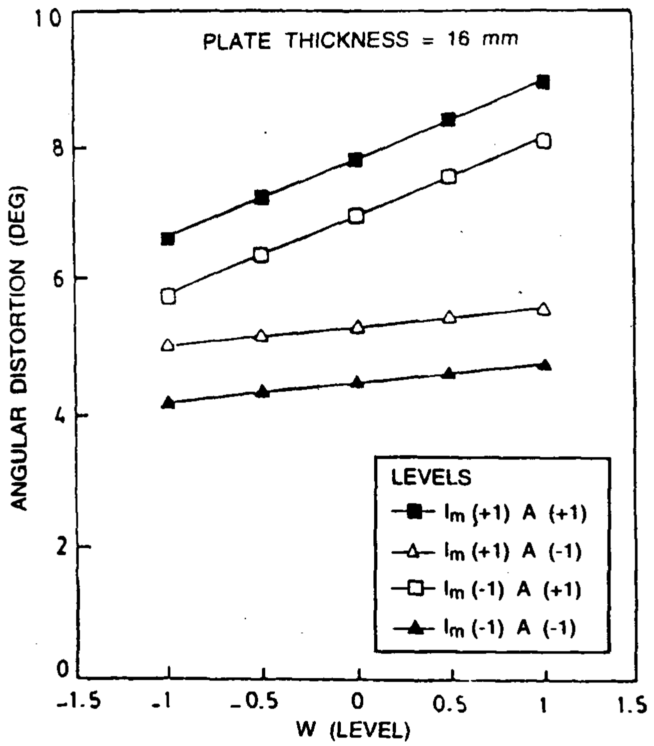


Fig. 5 : Effect of Welding Speed on Angular Distortion

FACTORS	LEVELS (+1)	LEVELS (-1)
Ip (Amps)	350	300
Im (Amps)	200	160
W (Cm/mn)	35	20
A (deg)	90	45

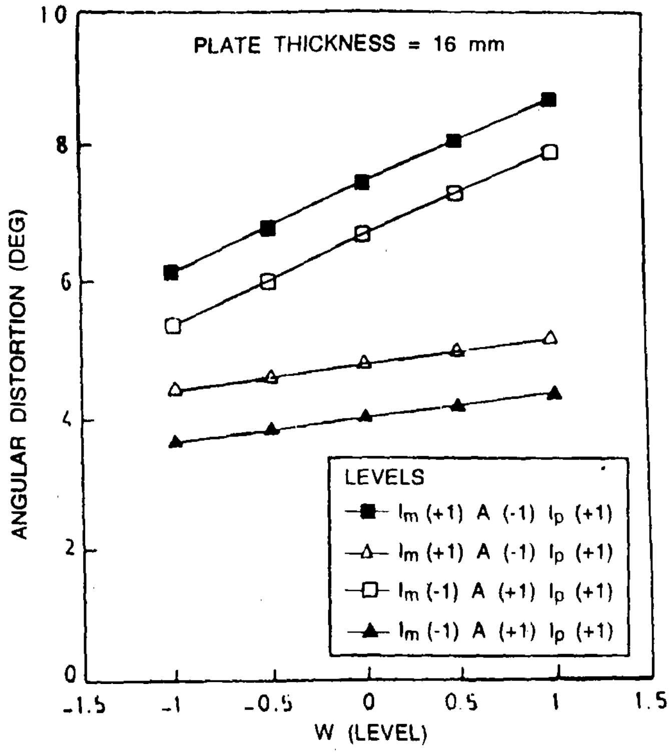


Fig. 6 : Effect of Welding Speed on Angular Distortion after Sealing Run

FACTORS	LEVELS (+1)	LEVELS (-1)
Ip (Amps)	350	300
Im (Amps)	200	160
W (Cm/mn)	35	20
A (deg)	90	45

With Ar-CO_2 Mixture as Shielding Gas

The main factor affecting angular distortion is the number of passes used for filling up the joint. No direct effect of different shielding gases was observed on angular distortion. But as the shielding gas composition was changed from industrially pure Argon to a mixture of Ar-CO_2, the filler wire feed rate increased substantially due to better metal transfer characteristics. For the cases reported at Sl. No. 1, 3, 6 & 7 of **Table V**, the average value of distortion is 3.57; compared to this, for the case reported at Sl. No. 14 of **Table IV,** the value of distortion is also 3.57. The number of passes used in all these cases was same. The average value of angular distortion for the cases reported at Sl. No. 8, 10 & 11 of **Table V** is 3.73; whereas the value of angular distortion is 4.618 for the case reported at Sl. No. 14 of **Table IV**. It may be observed that the difference in the value of angular distortion for the case reported at Sl. No. 9 of **Table V** & Sl. No. 13 of **Table IV** is 1.23 degree. This difference in the value of angular distortion is due to change in the number of passes. The average reduction in the value of angular distortion is 1.054 degree with a reduction of one pass. This reduction in the number of passes was possible because Ar-CO_2 gases supported a higher wire feed rate than industrially pure Argon gas without adversely affecting the mode of metal transfer.

CONCLUSIONS

1. Minimum angular distortion was achieved when both welding current and welding speed were kept at minimum.
2. With the change of shielding gas composition from industrially pure Argon to Ar-CO_2 mixture angular distortion decreased for 16 mm thick plates.
3. The average reduction in the value of angular distortion is 1.054 degree with a reduction of one pass.
4. The mathematical models developed may be used to control distortion for the range of welding variables used.

REFERENCES

1. Linnert E. G., Welding Metallurgy, 3rd Ed., Vol. 2, AWS, New York, pp. 109.
2. Okerblom N.O., The Calculation of Deformation of Welded Metal Structure, Mashgiz, Moscow, 1955 (Trans HMSO, London, 1958).
3. Watanabe, M. and Satoh, K., Effect of Welding Conditions on the Shrinkage and Distortion in Welded

Structures, Welding Journal, Vol. 40, No. 8, Research Supplement (1961), pp. 377s-384s.

4. Capel, L., Aluminium Welding Practice, British Welding Journal, Vol. 8, No. 5, 1961, pp. 245-248

5. You, S.Y., Ahn, S.C. and Jo, S.T., A Study of Weld Distortion in Steel Butt and Filler Welds made by Flux Cored Arc Welding, Recent Trends in Welding Science and Technology, TWR'89, Proc. of the 2nd Int. Conf. on Trend in Welding Research, Gattingburg, Tennesse, USA, 14-18 May, 1989, pp. 119-123.

6. Matsui, S., Investigation of shrinkage, Restraint Stresses and Cracking in Arc Welding, PhD Thesis at Osaka University, 1964, Japan.

7. Baysinger, F. R., Distortion Control in Welding of Aluminium Structures, Welding J., December, 1972, pp. 833-841.

8. Chihosks, R.A., Understanding Weld Cracking in Aluminium Sheet, Welding J., January, 1972, pp. 24-30.

9. Leggatt, R.H. and White, J. D., Predicting Shrinkage and Distortion in Welded Plate, Residual Stresses in Welded Construction and their Effects, Int. Conf., London, 15-17 Nov., Vol. 1, 1977, Welding Institute, Abington Hall, Cambridge, pp. 119-125.

10. Kihara, H., Masubuchi, K., and Matsuyama, Y., Effect of Welding Sequence on Transverse Shrinkage and Residual Stresses, Report No. 24, of Transportation Technical Research Institute, Tokyo, 1957.

11. Kihara, H., Masubuchi, K., and Ogura, Y., Radial Contraction and Residual Stresses in Circular Patch Weld, Parts I & II, Journal of the Society of Naval Architecture of Japan, 1956, 99, pp. 111-122 and 100, pp. 163-170.

12. Iwamura, Y., Reduction of Transverse Shrinkage in Aluminium Butt welds, M.S. Thesis, MIT, May, 1974.

13. Spraragen, W. and Ettinger, W.G., Shrinkage Distortion in Welding, Welding Journal Research Supplement, Vol. 29, Nos. 6 & 7, 1950, pp. 2925-2945 and 3235-3355.

14. Arya, S. K. and Parmar, R. S., Mathematical Models for Predicting Angular Distortion in CO_2-Shielded Flux Cored Arc Welding, JOM-3, Helsingor (Denmark), Dec. 19-27, 1986, pp. 240-245.

15. Davis, O.L., The Design and Analysis of Industrial Experiments, Macmillan Publications, Hafner. 1971.

16. Adler, Yu. P., Markova, E. V. and Granovsky, Yu. V., The Design of Experiments to Find Optimal Conditions, Mir Publishers, Moscow, 1975.