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MATHEMATICAL MODELLING TO PREDICT ANGULAR DISTORTION IN BUTT-WELDED STAINLESS STEEL 304 THIN PLATES

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Abstract: *Arc welding processes are characterized by the input of huge amount of heat into the workpieces. The heating and cooling cycles associated with this process are quite rapid and non-uniform in nature. This leaves different parts of the weldment subjected to non-uniform thermally generated stresses resulting in weld distortions. These distortions account for multiple rejections and expensive remedial procedures in MIG welding of thin plates, particularly in the butt joint configuration plus cause difficulty in assembling and spoil the aesthetic appeal of the product. Thus, it is crucial for the designer to be able to foresee the extent of these distortions to a certain level of accuracy so that pre-remedial steps can be taken while selecting the input parameters to minimize the final angular distortion. Thus, there is a need for a mathematical model capable of predicting the same. Hence in the present work, a mathematical model was developed using the statistical technique of Design of Experiments to predict these effects to minimize their consequences. Accordingly, an investigative work was carried out that involved carrying out a number ofexperimental runs in a structured manner. The material selected for the study is SS304 plates (2mm thick), as Stainless Steel recently is finding ever increasing demand in engineering and structural applications because of its many advantagesover low alloy steels. A mathematical equation was developed whose adequacy was checked using ANOVA technique. Response surface methodology was used to developgraphical representation ofdirect and interactive effects of input parameters on angular distortion.*

Key words: *stainless steel, angular distortion, input parameters, mathematical model, ANOVA.*

Matematičko modeliranje u cilju određivanja ugaonog krivljenja kod zavarivanja pod ravnim uglom tanke ploče od nerđajućeg čelika 304. *Postupke lučnog zavarivanja karakteriše unos ogromne količine toplote u radne komade. Ciklusi grejanja i hlađenja povezani sa ovim procesom su prilično brzi i neujednačeni. Zbog toga se različiti delovi obradka tokom zavarivanja izlažu nejednakim termički generisanim naponima što rezultira izobličenjem zavara. Ova izobličenja objašnjavaju višestruka odbacivanja i skupe korektivne postupke kod MIG zavarivanja tankih ploča, posebno u konfiguraciji zadnjeg zgloba, plus uzrokuju poteškoće u sastavljanju i narušavaju estetsku privlačnost proizvoda. Stoga je od presudnog značaja za projektanta da može predvidjeti opseg tih izobličenja do određenog nivoa tačnosti, tako da se mogu preduzeti koraci pre korekcije prilikom odabira ulaznih parametara, da bi se umanjilo krajnje ugaono krivljenje. Stoga postoji potreba za matematičkim modelom koji bi mogao da predvidi isto. Otuda je u ovom radu razvijen matematički model koristeći statističku tehniku dizajna eksperimenata kako bi se predvideli ti efekti i kako bi se smanjile njihove posledice. Shodno tome, izvršen je istraživački rad koji je uključivao sprovođenje više eksperimentalnih ogleda na strukturiran način. Materijal odabran za studiju su ploče SS304 (debljine 2 mm), jer nehrđajući čelici u poslednje vreme imaju sve veću potražnju u inženjerskim i konstrukcijskim primenama zbog mnogih prednosti u odnosu na niskolegirane čelike. Izrađena je matematička jednačina čija je adekvatnost proverena pomoću ANOVA tehnike. Metodologija odzivne površinske korišćena je za razvoj grafičkog prikaza direktnih i interaktivnih efekata ulaznih parametara na ugaonu distorziju.*

Ključne reči: *nerđajući čelik, ugaona distorzija, ulazni parametri, matematički model, ANOVA.*

1. INTRODUCTION

A conventional fusion welding technique, MIG welding, is an extensively employed joining process for the production and assembly of various end products in the aerospace, aviation, shipbuilding, construction, automotive sector and general fabrication works [1]. MIG welding is characterized by the formation of an electric arc between a consumable wire electrode and base metal providing the heat input for the melting of both. This is followed by the solidification process for the formation of highly efficient joints. The use of inert gases as shielding gases ensure the protection of the weld zone. However, the uneven temperature distribution during welding and the subsequent non-uniform cooling results in the generation of thermal stressesplus the material plastic deformation at high temperatures are the primary causes of welding distortions and residual stresses in the parent material [2,3]. These considerably degrade the quality of the weld, reduce the service life of the welded structure andcause critical failures. Thus, it is of paramount importance to quantify the extent of these distortions and stresses and to make accurate predictions for the same, to facilitate the implementation of remedial measures. Research works by Rosenthal [4] were the first to propose a mathematical model of the moving heat source considering concentrated point heating and a quasi-stationary state. Subsequently several heat source models were developed and used in welding simulation to predict distortions and residual stresses [5,6]. Welding of thin plates have been considered in the present study owing to its wide use in the automotive and food processing industry for the production of light weight structures with high strengths in tension, compression, shear; resistance to creep, fatigue failure, etc. Many researchers like Deng and Murukawa [7], Tsai CL [8] have published work on the prediction of welding distortions and stresses during MIG welding of thin plates by using FEM. However, majority of all these researches have been conducted for low carbon steels and considering the rapid transition of the industry to using stainless steels and high strength alloys; relatively limited literatureon welding related investigations exists for the same, thus the present work has been carried out with the objective of acquiring a quantitative insight into some of the welding aspects of Stainless steel. Stainless steel 304, an austenitic grade steel owing to its excellent formability, deep drawability, weldability and superior mechanical and physical properties as represented by Table 1 and 2 respectively hasextensive applications. Its exceptional resistance to corrosion even in adverse environments makes it suitable for the manufacturing of various industrial products like automotive fuel tanks, catalytic convertors and turbochargers, chassis for vehicles, architectural panelling, railings, structural components etc [9]. Due to the criticality, scale and the variety of its uses, SS304 has been considered for the present study.This work has specifically focussed on the investigation of angular distortion (shown by Fig.1) and its prediction under different combinations of input variables as angular distortion is more pronounced in case of butt-welded thin sheets and causes more rejections than any other type of distortion. In the current study, a mathematical model has been developed using statistical technique of Design of Experiments to predict the same.

GRADE	Mechanical Properties	UTS (MPa)	YS(MPa)	%EL	Hardness (HRB)
304	ASTM A240	≥515	≥205	≥40	≤92

Table 1. Mechanical Properties

GRADE	Density (kg/m^3)	Modulus of Elasticity (GPa)	Thermal Conductivity (W/m °C)	Coefficient of Thermal Expansion (µm/m/ °C)	Electrical Resistivity (µΩm)
304	7910	195	16.3	17.3	0.72

Table 2. Physical Properties

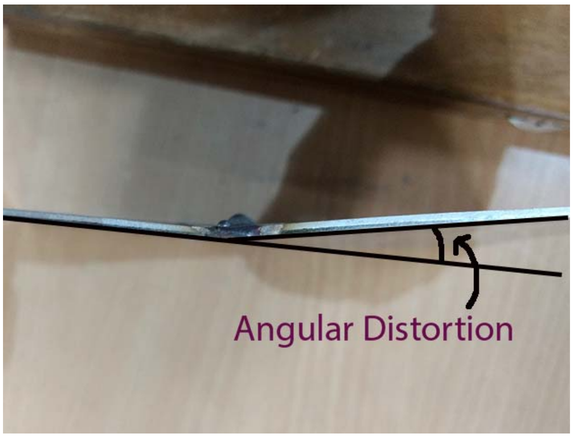

Fig. 1. Angular Distortion

2. EXPERIMENTAL SETUP

The experimental setup used in the present investigative work consists of a MIG welding power source, rectifier type with open circuit voltage of 45 Volts and rated current capacity of 400 amperes, 100 % duty cycle and flat V-I Characteristics. Industrially pure argon gas is used for shielding and the flow rate is maintained at about 15 litres/min throughout the experiment. To maintain the desired welding speed and ensure reproducibility of results, a mechanized welding unit is used whichprovides a stepless control of carriage speed from 0 to 50 cm/min. A variable frequency drive has been used to control the speed of carriage motor. The complete setup is shown in Fig.2.

Fig. 2. Experimental Setup

3. PLAN OF INVESTIGATION

The research work has been carried out in accordance to the following steps:

1. Identification of input parameters and their operating ranges
2. Development of the design matrix
3. Measuring the angular distortion
4. Developing the mathematical model
5. Checking the adequacy of the developed model
6. Results and their interpretation
7. Conclusions

3.1 Identification of input parameters and their operating ranges

On the basis of previous experience, literature survey and trial experiments, it was found that wire feed rate, voltage and welding speed were having significant effect on the resulting angular distortion. Furthertrial runs were carried out to estimate the working ranges of these parameters by observing the following:

- No spatters on the weldments
- No visible cracks, undercut or burn-through
- No visible signs of porosity

The parameters were taken at three levels. The estimated ranges of these parameters were quoted as high level, intermediate level and low level, indicated by +1, 0 and -1 respectively. These values are shown in Table 3.

Input Parameter	**Symbol**	**Unit**	**Levels**		
			-1	0	+1
Wire feed rate	**C**	m/min	4	6	8
Voltage	**B**	Volts	16	18	20
Welding speed	**A**	cm/min	40	45	50

Table 3. Input Parameters

3.2 Development of Design Matrix

The Design Matrix comprising of twenty experimental runs [(2^3) + (2*3) + 6 = 20] was developed using the central composite face centred technique. (2^3) represents the full factorial points, the star points are represented by (2*3) and additional 6 runs at zero level of all the input parameters have been added with the aim of improving the precision of the model. Twenty experimental runs conforming to the design matrix as shown in Table 4 were conducted in identical conditions.

Std	**Run**	**A: Speed (cm/min)**	**B: Voltage (volts)**	**C: Feed rate (m/min)**	**Response: Angular Distortion (degree)**
5	1	-1	-1	1	7.5
16	2	0	0	0	5.8
20	3	0	0	0	6.2
6	4	1	-1	1	6.4
3	5	-1	1	-1	7.4
1	6	-1	-1	-1	5.9
4	7	1	1	-1	6.6
18	8	0	0	0	6.1
17	9	0	0	0	6.5
10	10	1	0	0	7.3
7	11	-1	1	1	8.8
11	12	0	-1	0	6.4
14	13	0	0	1	6.3
2	14	1	-1	-1	5.2
8	15	1	1	1	7.5
19	16	0	0	0	6.8
15	17	0	0	0	6.4
13	18	0	0	-1	6.1
9	19	-1	0	0	7.8
12	20	0	1	0	6

Table 4. Design Matrix

3.3 Measuring the Angular Distortion

The measurement of the angular distortion of each plate was carried out with the help of a height gauge fitted with a dial test indicator; with the base of the height gauge placed on the surface plate. The weldment was placed with packing under one of the plates, on the surface plate with slight weight on the plate so that the other plate is lowered by an amount equal to the angular distortion. The zero count of height gauge is set by touching the probe of the dial test indicator to the flat plate. The height gauge is then moved and the slider of the height gauge is lowered till the tip of the dial test indicator plunger touches the edge of the lowered plate of the weldment giving height h_1. The weldment is now turned by 180° and the same procedure is repeated to measure the height of the other edge as h_2. The average of h_1 and h_2 gives the lowered height of the plates h.
Now using the relation,

$$\sin\theta = \frac{h}{l}$$

where l is the width of the plate, the angular distortion is calculated and recorded as shown in Table 4.

Fig. 3. Measuring the angular distortion

3.4 Developing the Mathematical Model

The response parameter of angular distortion can be represented in the functional form as below:

Angular distortion = f (A, B, C)

where the meanings of A, B, C are as explained above.

The general regression equation for the present case can be represented as:

$$\text{Response} = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{12} AB + \beta_{13} AC + \\ + \beta_{23} BC + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2$$

where,
β_0 is the constant of the model;
β_1, β_2, β_3 are the regression coefficients for the main effects;
β_{13}, β_{23}, β_{11} are the regression coefficients for interaction effects;
β_{11}, β_{22}, β_{33} are the regression coefficients for quadratic terms;

The actual regression equation expressing the mathematical relationships between response and input parameters, after dropping the insignificant terms is given below.

Angular Distortion = $6.36-0.4400A + 0.4900B + 0.5300C - 0.0375AB - 0.1125AC - 0.0625BC + 1.09A^2 - 0.2591B^2 - 0.2591C^2$

3.5 Checking the adequacy of Developed Model

The adequacy of the developed model can be checked using the ANOVA technique. Since ANOVA involves large calculations which become cumbersome and impractical by manual methods, a Statistical software called Design Expert was used to facilitate error free and effective ANOVA analysis which has been given in the form of Table 5.

From the results depicted in Table 5, the adequacy of the model is proved to be significant as the calculated F is more than the tabulated value of F. Secondly, the lack of fit is also insignificant. This claim is further substantiated by the high R^2 and adjusted R^2 values as given in Table 6.Further the scatter diagram plotted by the software between actual and the predicted values also confirm the same because of the closeness of all the points around the line of fit as shown in Fig 4.

Source	Sum of Squares	DF	Mean Square	F-value	P-value	
Model	10.92	9	1.21	5.00	0.0096	**significant**
A-speed	1.94	1	1.94	7.98	0.0180	
B-voltage	2.40	1	2.40	9.89	0.0104	
C-feed rate	2.81	1	2.81	11.57	0.0068	
AB	0.0113	1	0.0113	0.0463	0.8339	
AC	0.1013	1	0.1013	0.4171	0.5329	
BC	0.0313	1	0.0313	0.1287	0.7272	
A^2	3.27	1	3.27	13.48	0.0043	
B^2	0.1846	1	0.1846	0.7605	0.4036	
C^2	0.1846	1	0.1846	0.7605	0.4036	
Residual	2.43	10	0.2428			
Lack of Fit	1.83	5	0.3655	3.05	0.1235	**not significant**
Pure Error	0.6000	5	0.1200			
Cor Total	13.35	19				

Table 5. ANOVA

Std. Dev.	0.4927	**R²**	0.8182	**Std. Dev.**
Mean	6.65	**Adjusted R²**	0.6545	**Mean**
C.V. %	7.41	**Predicted R²**	-0.0994	**C.V. %**
		Adeq Precision	8.3814	

Table 6. R^2 and adjusted R^2 values

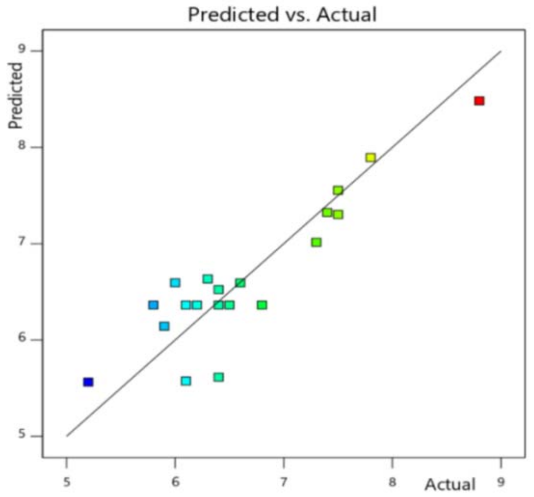

Fig. 4. Scatter diagram between predicted and actual values

3.6 Results and their Interpretation

The results of the investigation carried out are given in the graphical form from Fig. 5 to 10. The interpretation of these results is divided into two categories namely; direct effects and interaction effects with their explanation as follows:

3.6.1 Direct effect of welding speed on angular distortion

Fig.5 depicts the direct effect of welding speed on angular distortion.

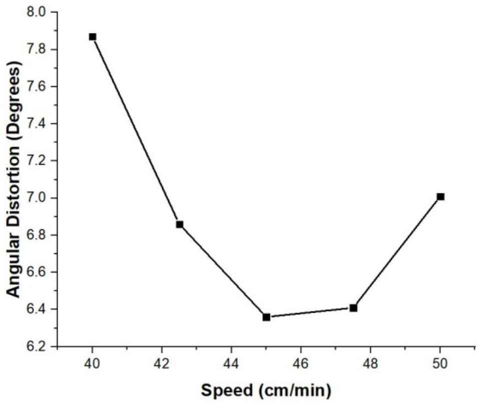

Fig. 5. Direct effect of welding speed on angular distortion

It is clear from the figure that the angular distortion decreased with the speed but later increased slightly with the increase of welding speed. The probable reason is, with the increase in speed the amount of heat input per unit length decreases which leads to lesser thermally generated distortion in the weldment. The reason for increase in angular distortion slightly after welding speed of 45cm/min could be attributed to the interacting effects of other parameters.

3.6.2 Direct effect of voltage on angular distortion

Angular distortion increased with an increase in the input voltage as shown in Fig. 6. The probable explanation for this could be, with the increase in arc voltage, the heat input increased along with the spreading effect of the arc which increases the angular distortion in the final weldment.

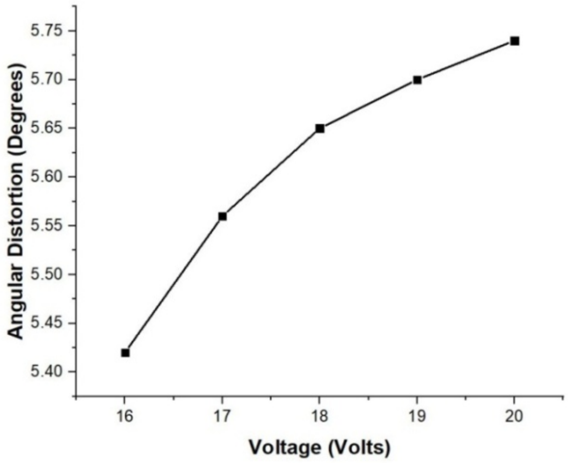

Fig. 6. Direct effect of voltage on angular distortion

3.6.3 Direct effect of wire feed rate on angular distortion

Fig. 7 depicts the direct effect of wire feed rate on angular distortion. For a constant voltage, the arc length is constant. So, with increasing wire feed rate, the current must also increase to melt the excess wire, thus maintaining a constant arc length. But with increasing current, the heat input increases which leads to higher thermally generated distortion in the weldment.

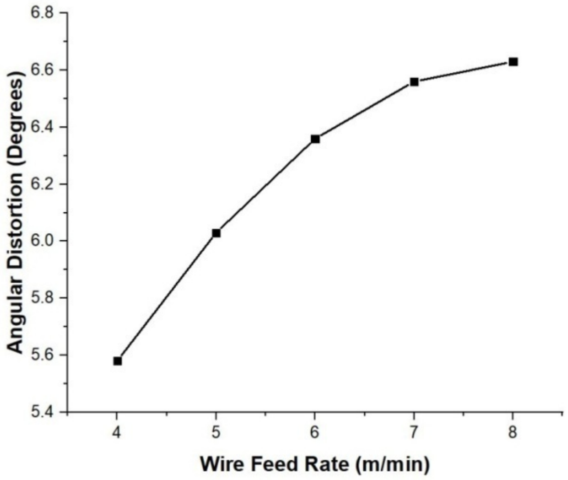

Fig. 7. Direct effect of wire feed rate on angular distortion

3.6.4 Interaction effects of voltage and welding speed on angular distortion

From the Fig. 8, it is clear that for all values of welding speed, the angular distortion increases with voltage whereasfor all values of input voltage the angular distortion first decreased significantly and later increased slightly with welding speed because of the reasons already mentioned in section 3.6.2. The minimum value of angular distortion is obtained at minimum voltage and moderate speed. The maximum value of angular distortion is obtained at maximum voltage and minimum speed.

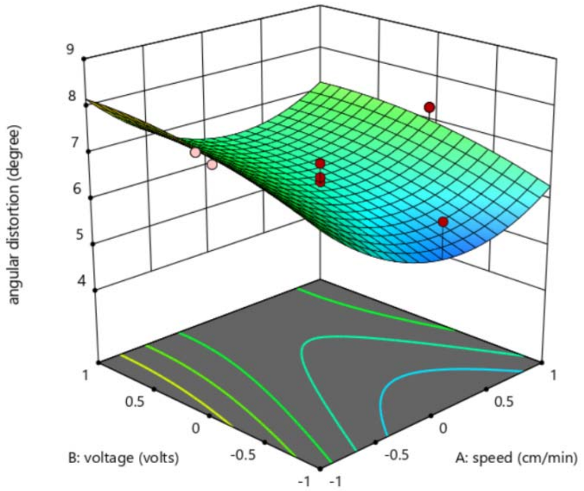

Fig. 8. Interaction effects of voltage and welding speed on angular distortion

3.6.5 Interaction effects of feed rate and welding speed on angular distortion

From the Fig.9, it is clear that for all values of feed rate, the angular distortion initially decreased significantly and afterwards increased slightly with welding speed. Whereas for all values of welding speed, the angular distortion increased with feed rate for the reasons already mentioned in Section 3.6.3. The minimum value of angular distortion is obtained at moderate speed and minimum feed rate. Whereas the maximum value of angular distortion is obtained at maximum feed rate and minimum speed.

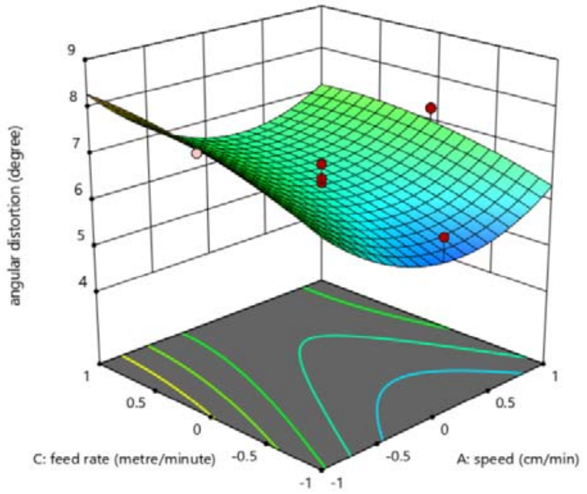

Fig. 9. Interaction effects of feed rate and welding speed on angular distortion

3.6.6 Interaction effects of feed rate and welding speed on angular distortion

From the Fig. 10, it is clear that for all values of feed rate, the angular distortion increased with voltage. Whereas for all values of voltage, the angular distortion increased slightly with feed rate for the reasons already mentioned in Section 3.6.3. The minimum value of angular distortion is at minimum voltage and minimum feed rate. Whereas the maximum value of angular distortion is obtained at maximum feed rate and maximum voltage.

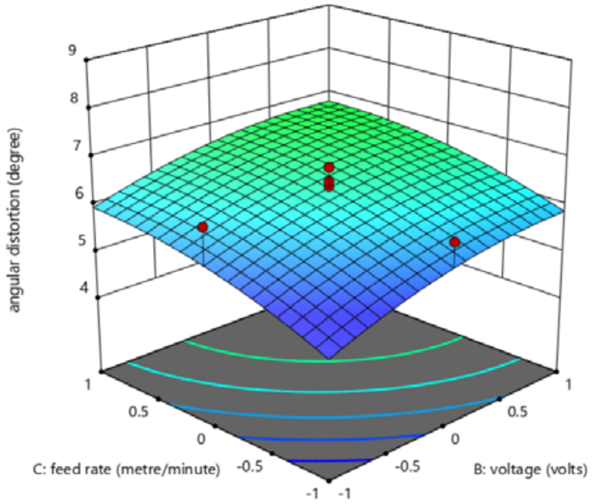

Fig. 10. Interaction effects of voltage and feed rate on angular distortion

4. CONCLUSION

The following conclusions can be drawn from the investigative work carried out so far;

- The central composite face centred design technique for designing the experiments was found to be useful for carrying out such investigative works.
- The wire feed rate was found to have a positive effect on angular distortion.
- The voltage was found to have a positive effect on angular distortion.
- The welding speed was found to have a negative effect on angular distortion.
- The wire feed rate and voltage were found to have positive effect on angular distortion.A maximum angular distortion of 6.8° was obtained at maximum values of voltage and feed rate. A minimum angular distortion 4.8° was obtained at minimum values of voltage and feed rate.
- Wire feed rate was found to have positive effect and speed was having a negative effect on angular distortion. A maximum angular distortion of 8.3° was obtained at maximum and minimum values of wire feed rate and welding speed respectively. A minimum angular distortion of 5.6° was obtained at minimum and intermediate values of wire feed rate and welding speed respectively.
- Voltage was found to have positive effect and speed was having a negative effect on angular distortion. A maximum angular distortion of 8.1° was obtained at maximum and minimum values of voltage and welding speed respectively. A minimum angular distortion of 5.6° was obtained at minimum and intermediate values of voltage and welding speed respectively.
- No visible defects were found in all the weldments.

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