Robust Design of Dissimilar Stainless Steel Joining

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ABSTRACT

Robustness is a key strategy for achieving high quality. There were different approaches to robust design namely inner-outer array approach advocated by Taguchi, the dual response approach using response surfaces and the tolerance analysis approach which is also through response surfaces.

This paper reports on a study that has been taken up to develop the robust design by dual response and tolerance analysis approaches for understanding the friction welding characteristics of austenitic stainless steel - ferritic stainless steel dissimilar metal welds.

Key words: Austenitic stainless steel, Ferritic stainless steel, Friction weld, Robust, Taguchi Method

INTRODUCTION

Austenitic stainless steels are used extensively in chemical, pertrochemical and Nuclear Industries because of their resistance to corrosion and good mechanical properties at elevated temperatures. Ferritic stainless steels possess high thermal conductivity and low thermal expansion and hence are particularly suitable for use in heat exchanger tubing and cladding.

Austenitic stainless steels are easily weldable through conventional fusion welding processes while ferritic stainless steels exhibit grain coarsening due to the absence of phase transformation from the liquid to solid at room temperature[1]. Dissimilar metal combination between ferritic stainless steel and austenitic stainless steel is commonly employed in Ti Cl_4 reduction retorts. Joining of these steels is considered to be a major problem due to differences in their properties and may lead to crack formation at the interface and also failure in service[2]. Friction welding is a possible solution for these problems.

Robustness is a key strategy for achieving high quality. There were different approaches to robust design namely inner-outer array approach advocated by Taguchi, the dual response approach using response surfaces and the tolerance analysis approach which is also through response surfaces[3,4].

This paper reports on a study that has been taken up to develop the robust design by dual response and tolerance analysis approaches for understanding the friction welding characteristics of austenitic stainless steel ferritic stainless steel dissimilar metal welds.

EXPERIMENTAL WORK

Parent metals

The parent metals employed in this study are AISI 304 austenitic stainless steel and AISI 430 ferritic stainless steel. Their chemical composition and mechanical property (ultimate tensile strength) are given in Table 1.

Friction welding

In the friction welding process, one weld piece is rotated while another is axially aligned and held stationary. The pieces are brought together and axial pressure is applied until friction heats the interface to a forging temperature. Rotation stops while forging pressure is applied to complete the weldment.

Welding was performed on a continuous drive friction welding machine 15 KN capacity at a speed of 1500 rpm (Figure 1). Friction force and forge force are the two input parameters varied while making the joints. Trail runs are conducted to arrive at range of these parameters which give defect free joints. The targets of the input parameters are given Table 2. A typical welded joint is shown in Figure

Mechanical properties evaluation

Tensile test is conducted on universal testing machine after creating a notch at the center of the weld on standard test specimen since failures occurred outside the weld on plain tensile specimens (Figure 3).

Robust design

Dual response approach involves running a response surface study where both the average and standard deviation of the output are analysed. In this approach it is assumed that the objective is to simply minimize the variation[5].

The tolerance analysis approach starts with a response surface study of the output i.e. average, with an objective to meet the target. The optimal values are obtained by applying variation transmission analysis[5].

RESULTS AND DISCUSSIONS

The strength of the welded joints has been evaluated at the chosen input parameters which are given in Table 3 and 4. At each of the target value eight reading are taken and have been used in computing the average and standard deviation. Table 5 depicts the final values of average and standard deviation of strength of the joints.

Quadratic polynomials were fit to these values using regression analysis. The equation is in the form

$$b_0 + b_1 t_{xi} + b_2 t_{xi}^2$$

where b_0, b_1, b_2 are coefficients and t_{xi} is the target parameter. The coefficients are estimated from the respective output data i.e. average or standard deviation (Y) and design matrices.

The design matrix (X) is in the form

$$\begin{bmatrix} 1 & t_{1xi} & t_{1xi}^2 \\ 1 & t_{2xi} & t_{2xi}^2 \\ 1 & t_{3xi} & t_{3xi}^2 \end{bmatrix}$$

and coefficients are computed[6] by using the matrix algebra principles $(X^TX)^1$ (X^TY). The resulting equations for the average and standard deviation of strength of joints are given in Table 6.

Dual response approach

Robust design by this approach is embarked upon with an objective of minimizing the variation[4]. An estimate of target of the minimum variation is obtained by taking the partial derivative of the equations for the standard deviation given in Table 6

ie $\left[\frac{\partial \sigma y_{x1}}{\partial t_{x4}}\right]$ =0, $\left[\frac{\partial \sigma y_{x2}}{\partial t_{x2}}\right]$ =0.

It gives in optimal target values t_{x1}=4.91 and t_{x2} = 10.38 and the corresponding variation computed is given in Table 7.

3.2 Tolerance analysis approach

In this approach the equations of average only be taken into consideration and tolerance analysis is performed on them. A typical computation procedure[5] for forge force t_{x2} is given below.

The equation for forge force y_{x2} is given by

$$y_{x2} = 153.15 + 84.86 t_{x2} - 3.66 t_{x2}^2 \quad (1)$$

The equation (1) is differentiated twice successively,

$$\frac{dy_{x2}}{dt_{x2}} = 84.8 - 7.32 t_{x2}$$ and

$$\frac{d^2 y_{x2}}{dt_{x2}^2} = -7.32$$

Plugging these values into the squared standard deviation of y_{x2} equation, with $\sqrt{\frac{8}{3}}$ as standard deviation of input target variable results in

$$\sigma y^2 = (84.8 - 7.32 t_{x2})^2 \ \sigma 2^2 + \frac{1}{2}(-7.32)\sigma 2^4$$

$$= (84.8 - 7.32 t_{x2})^2 \frac{8}{3} + \frac{1}{2}(-7.32) \times \frac{64}{9} \quad (2)$$

An estimate of tx_2 that optimizes the equation (2) is obtained by taking the partial derivatives as computed in dual response approach which results in t_{x2}=11.3; Similarly t_{x1} is found to be 4.3.

The results are compiled in Table 7 which portrays the estimates of target and the variation by these approaches. The friction force was taken in the range 4 to 6 KN for making the joints and the optimal value is 4.3 KN by Tolerance analysis approach and 4.91 KN by dual response approach while the forge force was in the range of 8 to 12 KN and the optimal values are 11.3 and 10.38 KN respectively. These values are implemented for making robust joints and the strength of such joint yielded is 672 Mpa.

CONCLUSIONS

The objective of robustness is making the product and process less sensitive to variation of the key inputs. Hence the results of the dual response and tolerance analysis are taken in tandem to fix up the input targets which are often called variation inducting parameters. The variation is least corresponding to the lower Standard deviation. The optimal conditions of the input targets are found to be 4.91 KN for frictional force and 11.3 KN for forge force to be operated during welding process. These conditions were employed simultaneously and joints between the dissimilar stainless steel metals are made. The optimal strength of the joint is found to be 672 MPa.

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Figure1: Friction welding machine

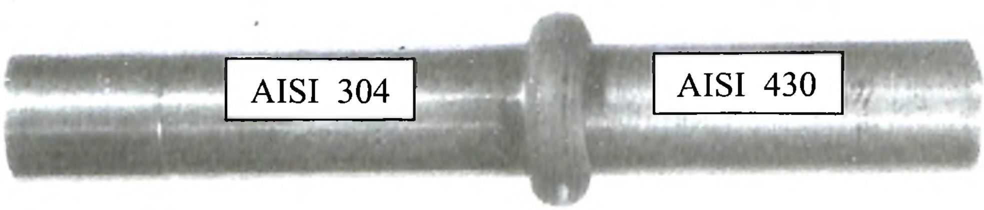

Figure 2: Friction welded joint

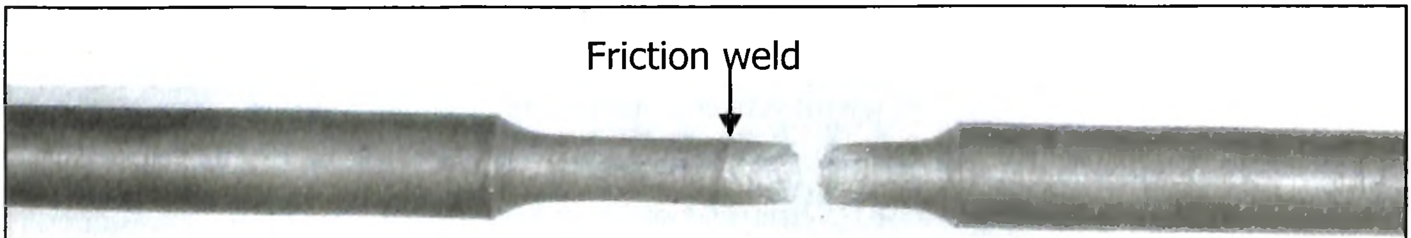

Figure 3: Friction welded tensile test specimen after test

Table 1: Chemical composition and properties of parent metals

	C	Si	Mm	Cr	S	P	Ni	UTS (Mpa)
AISI 430	0.06	0.4	0.4	17.0	0.03	0.04	-	488
AISI 304	0.06	0.32	1.38	18.4	0.28	0.4	8.17	600

Table 2: Input parameters (target)

S. No.	Friction force (KN)	Forge force (KN)
1	4	8
2	5	10
3	6	12

Table 3: Data with friction force

Forge force (Target) t_{x1}(KN)	Notch tensile Strength (Mpa)			
$t_{1x1}=4$	668 630	610 629	663 607	616 619
$t_{2x1}=5$	658 632	625 648	630 615	650 630
$t_{3x1}=6$	647 635	640 669	600 628	689 637

Table 4: Data with forge force

Forge force (Target) t_{x2}(KN)	Notch tensile Strength (Mpa)			
$t_{1x2}=8$	668 647	630 635	663 600	607 628
$t_{2x2}=10$	640 625	642 650	638 612	640 632
$t_{3x2}=12$	609 630	638 671	617 618	680 646

Table 5: Estimates of the average and standard deviation

Estimate (y)	tx1			tx2		
	4	5	6	8	10	12
Average	630.3	636.0	643.2	597.3	634.9	638.6
Standard deviation	21.7	13.6	24.9	43.8	11.0	25.7

Table 6: Regression equations for average and standard deviation

Parameter	Average	Standard deviation
Friction force (t_{x1})	$y_{x1} = 621.75 + 0.775t_{x12} - 0.725t_{x1}$	$\sigma y_{x1} = 248.7 - 95.67t_{x1} + 9.73t^2_{x1}$
Forge force	$y_{x2} = 153.15 + 84.86t_{x2} - 3.66t^2_{x2}$	$\sigma y_{x2} = 649.5 - 123.15\, t_{x2} + 5.93\, t^2_{x2}$

Table 7: Estimates of target and corresponding standard deviation

Approach	Target	Standard deviation
Dual response	$t_{x1}=4.91$ $t_{x2}=10.38$	$\sigma y_{x1}=13.5$ $\sigma y_{x2}=79.4$
Tolerance analysis	$t_{x1}=4.3$ $t_{x2}=11.3$	$\sigma y_{x1}=17.2$ $\sigma y_{x2}=15.7$