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Development Of Mathematical Model To Predict Diffusion Layer Thickness And Interface Hardness Of Diffusion Bonded Al-Cu Bimetallic Joints By P/M Route

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Abstract: In this investigation, pure aluminium (Al) and pure copper (Cu) plates prepared by powder metallurgy (P/M) technique were bonded by diffusion bonding process. From the literature, it was identified that the predominant diffusion bonding process parameters such as bonding temperature, holding time and bonding pressure influence the diffusion layer thickness and interface hardness of diffusion bonded joints. In this investigation an attempt was made to formulate mathematical model to predict the diffusion layer thickness and interface hardness of diffusion bonded bimetallic joints of pure Al/Cu incorporating the above parameters using statistical tools such as design of experiments, analysis of variance and regression analysis. The formulated empirical relationships can be used to predict the above diffusion layer thickness and hardness of Cu/Ni bimetallic joints at 95% confidence level.

Keywords: Powder metallurgy, Diffusion bonding, Design of experiments, Analysis of variance and Regression analysis.

1. INTRODUCTION

Diffusion bonding is a advanced solid state metal joining process that is applied for electronic, aerospace, automotive industries and nuclear applications [1]. Joining these dissimilar materials by conventional welding technique is hurdle, as it causes many problems such as thermal cracking, easy formation of brittle itermettalic compounds. These problems can be overcome by diffusion bonding technique that is also used in the production of high quality joints without post weld machining. Therefore, this technique is preferred to join these dissimilar materials without many difficulties. This metal joining process is dependent on bonding temperature, holding time, and bonding pressure and these parameters affect the interfacial structure, and the quality of bonds [2].

Many of research works have been carried out to understand the effect of diffusion bonding parameters on mechanical and metallurgical characteristics of dissimilar joints of wrought alloys [3-9]. All the above mentioned investigations were carried out on trial and other basis to attain optimum welding conditions. But there is no literature available to predict strength of joints on diffusion bonding of powder metallurgically (P/M) produced pure Cu and pure Al bimetallic joints. Hence, in this investigation, an attempt was made to develop empirical relationships to predict diffusion layer thickness and interface hardness of the Cu/Al bimetallic joints using statistical tools such as design of experiments (DOE), analysis of variance (ANOVA) and regression analysis.

2. EXPERIMENTAL WORK

Square shaped specimens (50 mmx50 mm) were manufactured from pure Al and pure Cu by powder metallurgical technique. The prepared specimen thickness of Cu was 3mm and Al was 5mm The specimens prepared by P/M technique were polished and chemically treated specimens were stacked in the die which was made by 316 L stainless steel. The specimens were heated up to the bonding temperature by induction furnace and the required pressure was simultaneously applied to the certain time. Thus, the bonding was completed and then the bonding samples were cooled to the room temperature before removal from the chamber of diffusion bonding machine. In

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this way, joints were fabricated using different combinations of bonding temperature, bonding pressure and holding time. The microstructure analysis was carried out to reveal the formation of diffusion layer at the interface of the joints using optical microscope and scanning electron microscope.

The copper side was etched by a solution containing ethanol, $FeCl_3$, concentrated HCl, whereas the aluminum side was etched by using Keller's solution to reveal the microstructure.

2.1. Finding the Working Limits of Diffusion Bonding Parameters

The predominant parameters influence mechanical and metallurgical characteristics and these were identified from the literature A large numbers of trial experiments were conducted to find the working limits of the above factors by varying one of the parameters and the other factors keeping in constant. The working range was fixed from the joints which should be free from external defects.

(i) When the bonding temperature was lower than 250 °C, the bonding was not occurred between Cu and Al plates since the above temperature was not sufficient to cause diffusion of atoms between these two materials (Fig. 1a).

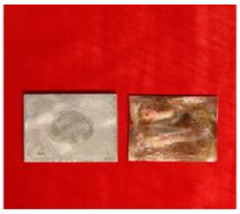
(ii) When he bonding temperature was higher than 450 °C, the bonding was not occurred between these materials because of the melting of pure Cu at this temperature (Fig. 1b).

(iii) If the bonding pressure was below 5 MPa, the bonding was not occurred as less number of contact points through which diffusion of atoms occur between the materials (Fig. 1c).

(iv) If the bonding pressure was higher than 20 MPa, the materials got plastically deformation and bulging at the edges of the materials (Fig. 1d).

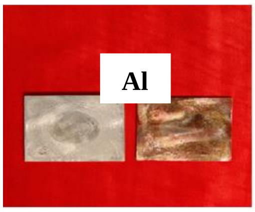
(v) If the bonding time was lesser than 5 minutes, bonding was not occurred because of the insufficient time for the diffusion atoms to take place between these materials (Fig. 1e).

(vi) If the bonding time was greater than 120inutes, excessive deformation occurred which led to the melting of pure Al (Fig. 1f).



(a): Temperature < 250 ºC

(b): Temperature > 450 ºC



(c): Pressure < 5 MPa

(d): Pressure > 20 MPa

(e): Time < 5 Min.

(f): Time > 120 Min.

Fig. 1: Photographs of fabricated bonds using lower and upper limit process parameter

2.2 Developing Experimental Design Matrix

The feasible limits of the variables were selected in such a way that all the combinations of the above materials should be bonded without any defects. As the limit of individual factor was wide, a central composite rotatable three-factors, five-level, central composite rotatable design matrix was chosen. The selected welding parameters and the levels are presented in **Table 1.** The experimental design matrix consisting 20 sets of coded condition and comprising a full replication three-factor factorial design of 8 points, 6 star points, and 6 center points was utilized **(Table 2).** The method of designing such matrix is dealt elsewhere [13]. The upper and lower limits of the parameters were coded as +1.682 and –1.682, respectively. The coded values for intermediate levels can be calculated from the following relationship [13]

$$X_i = 1.682\,[2X - (X_{max} + X_{min})] / (X_{max} - X_{min}). \quad (1)$$

Where,
X_i is the required coded value of a variable X and X is any value of the variable from X_{min} to X_{max}. X_{min}

is the lower level of the variable and Xmax; is the highest level of the variable.

Table 1: Feasible working limits of diffusion bonding parameters of Cu/Al bonds

No	Parameters	Notations	Units	Levels				
				-1.682	-1	0	1	1.682
1	Bonding temperature	T	^0C	266	300	350	400	434
2	Holding time	H	Minutes	30	45	60	75	90
3	Bonding pressure	P	MPa	10	12.5	15	17.5	20

Table 2: Experimental design matrix and responses of Cu/Al bonds

Exp. No	Coded values			Original values			Diffusion Layer Thickness	Interface Hardness
	T	H	P	T	H	P	DL	IH
1	-1	-1	-1	300	45	13	17	68
2	1	-1	-1	400	45	13	26	92
3	-1	1	-1	300	75	13	22	83
4	1	1	-1	400	75	13	31	114
5	-1	-1	1	300	45	18	20	73
6	1	-1	1	400	45	18	31	114
7	-1	1	1	300	75	18	25	88
8	1	1	1	400	75	18	37	126
9	-2	0	0	266	60	15	16	61
10	2	0	0	434	60	15	35	116
11	0	-2	0	350	35	15	21	81
12	0	2	0	350	85	15	28	108
13	0	0	-2	350	60	11	25	86
14	0	0	2	350	60	19	32	118
15	0	0	0	350	60	15	31	114
16	0	0	0	35	60	15	30	110
17	0	0	0	350	60	15	31	114
18	0	0	0	350	60	15	30	110
19	0	0	0	350	60	15	30	110
20	0	0	0	350	60	15	30	110

2.3 Recording the Responses (diffusion layer thickness and interface hardness)

As per the design matrix, twenty bimetallic joints were fabricated. The joints were sliced using wire cut electric-discharge machining (WEDM) process. The microstructure analysis was carried out at the interface region and the diffusion layer thickness was measured using the scanning electron microscopy. The interface hardness was also measured by using Vicker's hardness tester and the average of three values is presented in **Table 2.**

3. DEVELOPING EMPIRICAL RELATIONSHIPS

The responses functions (Y) are diffusion layer thickness (DL) and interface hardness (IH) and they are function of bonding temperature (T), bonding pressure (P) and holding time (H) and it can be expressed as in the mathematical form as below

DL = f{T,H,P} ; IH = f{T,H,P};

The second order polynomial (regression) equation used to represent the response surface 'Y' and the selected polynomial could be expressed as;

$$Y=b_0+b_1(T)+b_2(H)+b_3(P)+b_{11}(T^2)+b_{22}(H^2)+b_{33}(P^2)+b_{12}(TH)+b_{13}(TP)+b_{23}(HP) \quad (3)$$

where b_0 is the average of responses and b_1, b_2, $b_3 \ldots b_{23}$ are regression coefficients that depend on respective linear, interaction, and squared terms of factors. The value of the coefficient was evaluated using Design Expert Software (DOE) .After determining the significant coefficients at the (95% confidence level), the final relationships were developed using these coefficients and the final empirical relationships were developed to estimate diffusion layer thickness and interface hardness of diffusion bonded Cu/Al dissimilar joints are given below:

$$DL = \{ -126.55+0.47194(T)+1.09755(H) +1.51759 (P) - 4(TH) - 3(TP) - 3(HP) - 4(T^2) - 3(H^2) - 0.087495(P^2) \} \ \mu m \quad (4)$$

$$IH =\{-563.60 + 2.148(T)+3.892(H) +11.554(P) - 4(TH) + 0.024(TP) -0.033(HP) - 3(T^2) - 0.026 (H^2) - 0.503 (P^2)\} \ Hv \quad (5)$$

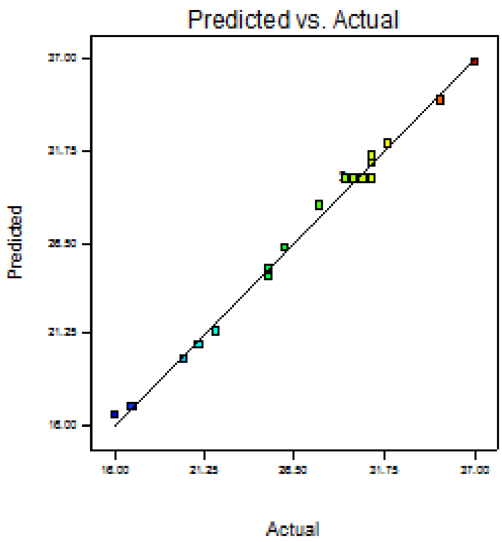
4. CHECKING ADEQUACY OF THE DEVELOPED RELATIONSHIPS

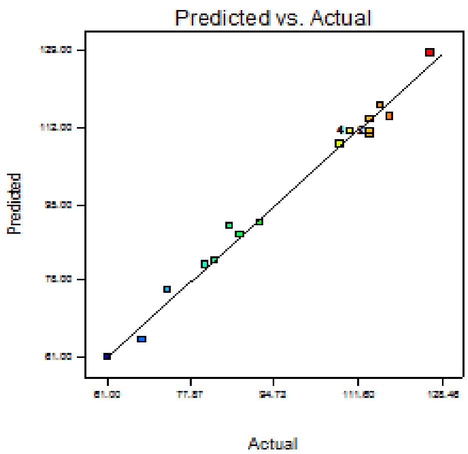
The adequacy of the developed relationships was tested by the analysis of variance (ANOVA) technique and the results of second order response surface model fitting in the form of analysis of variance are given in Tables 3. The determination coefficient (R^2) indicates the goodness of fit for the model. In this case, the values of the determination coefficient (R^2) indicate that the model does not explain only less than 5% of the total variations. The values of adjusted determination coefficient (adjusted R^2) are also high, which indicates a high significance of the model. Predicted R^2 is also made a good agreement with the adjusted R^2. Adequate precision compares the range of predicted values at the design points to the average prediction error. The relationships between actual and predicted responses and each observed responses of Cu/Al bonds are compared with the predicted responses calculated from the model and their respective correlation graphs are shown in **Fig. 2.** From the ANOVA table 3, the higher F ratio value implies that the respective term is more significant and vice versa. From the F ratio values it can be concluded that the bonding temperature is contributing more on diffusion layer thickness and interface hardness and it is followed by bonding pressure and holding time.

Table 3. ANOVA test results for Cu/Al bonds (to identify significant factors)

Source	Diffusion layer thickness (DL)		Interface hardness (IH)	
	F Value	p-value Prob >F	F Value	p-value Prob >F
Model	197.02	<0.0001*	83.70	<0.0001*
T	1118.94	<0.0001*	419.73	<0.0001*
H	225.80	<0.0001*	97.94	<0.0001*
P	174.05	<0.0001*	78.28	<0.0001
TH	0.36	0.5624	0.22	0.6466
HP	8.97	0.0134*	8.05	0.0177*
TP	0.36	0.5624	1.40	0.2646
T^2	106.92	<0.0001*	100.92	<0.0001*
H^2	159.13	<0.0001*	54.08	<0.0001*
P^2	12.37	0.0056*	15.91	0.0026*

*Values of "Prob > F" less than 0.0500 indicate model terms are significant.





(a) Diffusion layer thickness and (b) Interface hardness

Fig. 3 Correlation graphs for Cu/Al diffusion bonds

5.CONCLUSIONS

(i) Empirical relationships were developed to predict the diffusion layer thickness and interface hardness of diffusion bonded bimetallic joints of pure Cu/Al incorporating important parameters such as bonding temperature, holding time and bonding pressure. The developed empirical relationships can be effectively used to predict the diffusion layer thickness and interface hardness of the above bimetallic joints at 95% confidence level.
(ii) Bonding temperature was found to have greater influence on diffusion layer thickness and interface hardness of bimetallic joints of pure Cu/Al followed by bonding pressure and holding time.

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