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OPTIMIZATION OF PROCESS PARAMETERS IN DISSIMILAR EXPLOSIVE CLADDING THROUGH TAGUCHI METHOD

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ABSTRACT

Taguchi approach was employed to establish the significant process parameters viz., standoff distance, loading ratio and preset angle to enhance the tensile strength of aluminum-copper explosive clads. The experiments were conducted based on three factors, three-level Taguchi L9 orthogonal array. In addition, an empirical relation based on multiple regression analysis was developed to predict the tensile strength of Al-Cu explosive clads at 95% confidence level. The results indicate that standoff distance followed by loading ratio and preset angle has strong influence in achieving higher tensile strength of Al-Cu explosive clad. The microstructural characterization of Al-Cu explosive clads shows characteristic undulating interfaces.

Keywords: *Explosive cladding, dissimilar metals, Tensile strength, Taguchi approach and optimization.*

1. Introduction

Aluminum-copper clad plates directly replace solid aluminum or copper in many electrical, electronics and cookware applications owing to high thermal and electrical conductivity, superior heat dissipation, good soldering and electroplating properties [1]. Welding of aluminum-copper plates by conventional methods is not viable due to formation of undesirable intermetallic compounds, whereas, explosive cladding offers a feasible alternative to clad aluminum-copper plates devoid of intermetallics at minimum cost [2, 3].

In explosive cladding, the detonation of chemical explosive forces the flyer plate to collide with the base plate to craft a metallurgical strong bond in a short duration (<50μs). As explosive cladding is very rapid, the mechanical properties of explosive clads are dictated by the judicial selection of process parameters viz., loading ratio, preset angle, detonation velocity, surface finish and standoff distance [4]. The higher mechanical strength of Al-Cu explosive clads is desirable, though, it will be detrimental if parameters are not selected properly [1]. To aid in the selection of process parameters which dictates the mechanical properties, different methods viz., weldability window [5], design of experiment [4] and mathematical modeling [6] were employed by earlier researchers. However, the studies on developing a mathematical model to predict the tensile strength (elastic to plastic transition) of aluminum-copper explosive clad using Taguchi analogy is limited and is attempted herein.

In this study, the contribution of process parameters viz., loading ratio, preset angle and standoff distance in enhancing tensile strength (response) of Al-Cu explosive clad is attempted by employing Taguchi L_9 orthogonal array. In addition, a regression equation is developed using analysis of variance (ANOVA) and signal to noise (S/N) ratio to determine the priority order of process parameters in achieving higher tensile strength.

2. Determination of parametric limits

The identification of the process parameters (factors) which affect the tensile strength (response) is a significant step in design of experiments. Taguchi experimental design, an orthogonal array with three factors and three levels (L_9) was selected, and experiments were conducted as per the standard orthogonal array [7]. Manikandan et al. [8], cladded varied thickness titanium flyer plates with stainless steel base plates and optimized standoff distance of 5 mm-10mm. Raghukandan [4], while cladding copper-low carbon steel recommended inclined configuration for smaller dimensions. Kahraman et al.[9] cladded titanium-steel plates with varied loading ratio, R (mass of explosive/mass of flyer plate) and initial angle of inclination of 5 degree and reported formation of continuous molten layer at higher energetic conditions. The preliminary trial experiments lead to the following observations (1) tensile strength of clad reduces beyond a loading ratio, R of 1.0 following intermetallic formation, whereas, successful clad was not possible below a loading ratio of 0.6 (2) . When the standoff

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distance is reduced below 6 mm, kinetic energy is insufficient to form a clad, whereas formation of intermetallic compounds at interface is witnessed due to higher kinetic energy dissipation when the standoff distance was increased above 10 mm. The cladding parameters are standoff distance (S) in mm, loading ratio (R), preset angle (A) in degree, are tabulated in Table 1.

3. Experimentation

Aluminum (50 X 100 X 2 mm^3) and copper (50 X 100 X 8 mm^3) plates (chemical composition and mechanical properties of participant metals are given in Table-2 and Table-3 respectively) were explosive cladded in both parallel and inclined geometries using Sun 90 explosive (detonation velocity-4000 m/s). The explosive was placed above the flyer plate and electric detonator is positioned on one corner. On detonation, flyer plate (Al) collides with the base plate (Cu) obliquely to form a clad. The Al-Cu explosive clads were sectioned parallel to the detonation direction and the specimen for Ram tensile test were prepared as per ASTM A-264 [10] and is shown in Fig.1.a & 1.b. The tensile testing was conducted by compressing the ram into the annular space drilled out in the base in a (10T UNITEK-94100) universal testing machine by applying uni-axial load.

Table 1. Control parameters and their levels

Control parameter	Notation	Unit	Level 1	Level 2	Level 3
Standoff distance	S	mm	6	8	10
Loading ratio	R	-	0.6	0.8	1.0
Preset angle	A	degree	0	3	6

Table 2. Chemical composition (wt %) of participant metals

Material	Composition (wt. %)						
	Cu	Mn	Si	Mg	Zn	Fe	Al
Al	0.0292	0.0177	0.101	0.0169	0.0158	0.479	Bal
Cu	99.99	0.0002	0.0004	0.0001	0.00042	0.0032	0.001

Table 3. Mechanical properties of participant metals

Properties	Aluminum	Copper
Ultimate tensile strength (MPa)	60	210
Tensile stress, Yield (Mpa)	35	70
Elongation (%)	30	40

4. Results

4.1 Study of signal/noise ratio

The signal to noise ratio was calculated to determine the influence of each process parameters viz., loading ratio (R), standoff distance (S) and preset angle (A) on enhancing the tensile strength of Al-Cu explosive clad. The experimental results were converted into signal-to-noise (S/N) ratio values employing Eq. 1 using Minitab-16 statistical software. In this study, the S/N ratio was chosen based on larger-the-better, in order to maximize the Ram tensile strength (response) determined by,

$$\frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$$

Where ‘n’ is the repetitions in each trial (n=3) and ‘Y’ is the experimental tensile strength. The higher S/N value of the response denotes the optimum parameters as reported by earlier researchers [11,12]. From Table-4, it is observed that highest tensile strength (T) was obtained at standoff distance-6 mm, loading ratio-1.0, preset angle-6^0 (Exp.No.3; S/N = 38.99).

Fig.2 shows the main effects of the process parameters on the S, L and A for achieving higher tensile strength. The increase in standoff distance reduces the tensile strength, wherein tensile strength increases with loading ratio. The tensile strength of the Al-Cu explosive clad increases up to a preset angle of 3^o and tends to decrease with increase in preset angle. The optimum tensile strength is obtained at minimum standoff distance (6 mm-first level), higher loading ratio (1, third level) and preset angle of 3 degree (middle level).

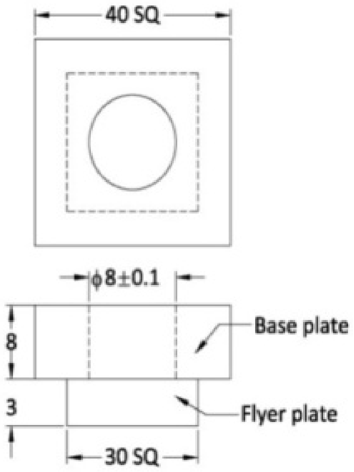


Fig.1(a) Specification of tensile specimen

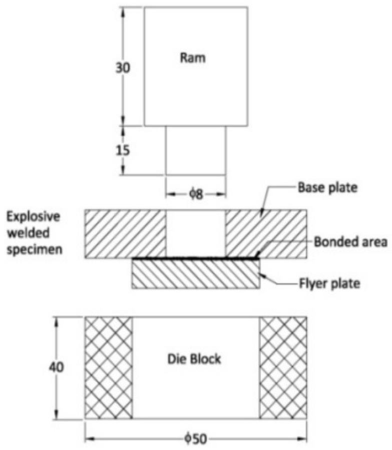


Fig. 1 (b) Ram tensile set up

4.2 Analysis of variance

ANOVA is a statistically based, object decision-making tool for detecting differences in the average performance of parameters under consideration[11]. The analysis of variance(ANOVA) establishes the relative significance of factors in terms of their percentage contribution in characterizing the tensile strength (response) of the Al-Cu explosive clads at 95% confidence (Table.5). F-test value at 95% confidence level was calculated to decide significant factors affecting the process bycomparing the F-ratio value of the parameter with the standard F table value (F0.05) at 5% significance level.Tricarrio et al. [12] opined that the process parameter is considered significant if F-ratio value is greater than F0.05. The considered process parameters significantly affecting the tensile strength (T) of Al-Cu explosive clads in the order of viz., standoff distance, loading ratio and preset angle (Table-5).

Table 4. Experimental Results and S/N ratio

Exp No.	S (mm)	R	A (degree)	T (MPa)	S/N Ratio
1	6	0.6	0	84	38.41
2	6	0.8	3	86	38.69
3	6	1.0	6	89	38.99
4	8	0.6	3	75	37.73
5	8	0.8	6	77	37.61
6	8	1.0	0	85	38.59
7	10	0.6	6	63	35.99
8	10	0.8	0	71	37.03
9	10	1.0	3	78	37.84

5. Discussion

5. 1 Percentage of contribution

The parameters standoff distance (S) and preset angle (R) contribute significantly on the enhancement of tensile strength of Al-Cu explosive clad. The percentage contribution of each process parameter and their magnitude of influence on enhancing the tensile strength of Al-Cu explosive clad are shown in Fig.3. The parameter standoff distance, S (69.8%) has the most dominant effect followed by the loading ratio (R) (27.8%) and preset angle (A) (7.8%) on tensile strength. However, standoff distance and loading ratio are statistically significant parameters at 95 % confidence level and the preset angle is insignificant on total variation.

5.2 Regression equation

Multiple regression technique is employed to ascertain the relationship prevailing among the variables. The multiple linear regressions take the following form.

$$Y= a+b_1X_1 +b_2 X_2+b_3 X_3+\ldots\ldots..+b_k X_k$$

Where Y is the dependent variable, which is to bepredicted. X_1, X_2, X_3... X_k are known variables on which the predictions are to be made and b_1, b_2, b_3 …b_k are the coefficients, the values of which are determined by the method of least squares. Multiple regression analysis is used to determine the relationship between dependent variable Ram tensile strength (T) with standoff distance (S), Loading ratio.

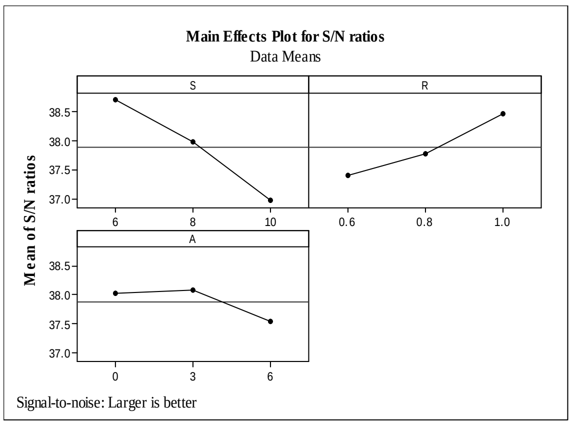


Fig.2 Main effects plot for S/N ratio on tensile strength

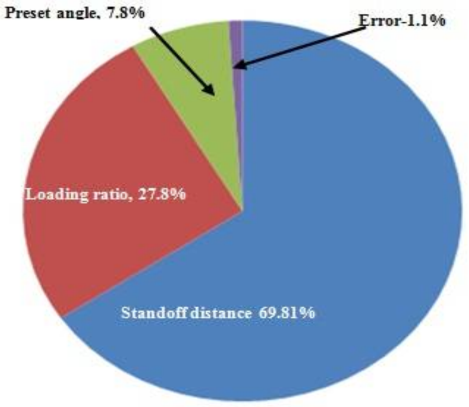


Fig.3 Percentage contribution of factors

(R) and Preset angle (A). The regression analysis is carried out in Minitab-16, and the regression analysis of the input parameters is expressed in linear equations as follows.

Tensile strength (T) = 93.4 - 3.92S + 23.3R - 0.667A

From the above equation the tensile strength (T) can be predicted for operational parameters within the selected range. In multiple regression analysis, the regression coefficient (R^2) is 0.920 indicating the fit of experimental data is satisfactory [13]. The developed mathematical model is in agreement with Raghukandan [4] who cladded copper-low carbon steel. The experimental Ram tensile strength is correlated with regression model (Eq.3) and is shown in Table. 6. The average error of 1.65% between experimental and statistical model is obtained indicating the developed model can predict the tensile strength of Al-Cu explosive clad at 95% confidence level. In the normal probability plot shown in Fig. 4 residuals for tensile strength fall close to the straight line and hence the model is integral with experimental values. The relationship between standoff distance (S) and loading ratio (R) for Al-Cu explosive cladding with respect to tensile strength (T) is shown in Fig. 5. The maximum strength is when standoff distance 6mm and loading ratio of 1.0.

5.3 Microstructure

The experimental results of aluminum-copper explosive cladding show interfacial wavy morphologies (Fig.6). Al-Cu explosive clad exhibit smooth undulating interfaces for a standoff distance of 6 mm, whereas formation of defects viz., 'Trapped jet' and molten layer is witnessed when standoff distance was increased to 8 mm or 10 mm (Fig.6) and results in reduction of the tensile strength of the clad. The microstructure of an Al-Cu explosive clad with a standoff distance 6 mm and a loading ratio of 0.6.

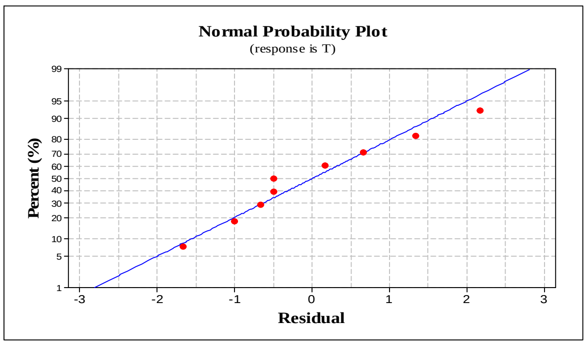


Fig.4 Normal probability plot residuals for tensile strength

Table 5. ANOVA table for tensile strength of Al-Cu explosive clad

Parameter	Degree of freedom	Sum of Square (SS)	Variance (V)	F-ratio	Percentage contributed % (P)
S	2	4.74	2.37	59.25	69.8
R	2	1.77	0.89	22.125	27.8
Angle	2	0.56	0.28	7	7.8
Error	2	0.08	0.04	--	1.1
Total	8	7.15	--	--	100

Fig.6 (a) resembles a straight interface. When the loading ratio and preset angle were increased to 0.8 and 3° respectively (Fig.6.b), the kinetic energy dissipated at the interface increases and amplitude and wavelength of the interface increases (amplitude-81 µm, wavelength-358 µm) as reported by Kahraman et al. [9].

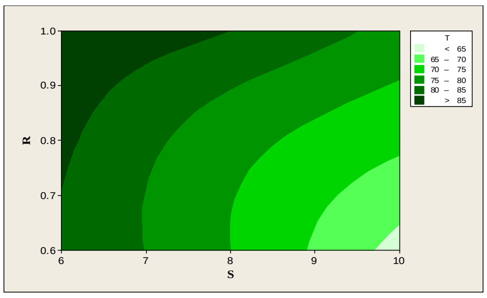


Fig. 5 Contour plot of tensile strength (S) Vs S,R

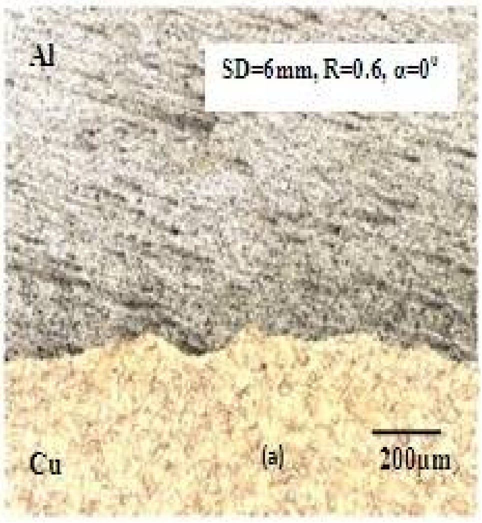
Formation of molten layer is witnessed on Al-Cu explosive clad interface followed by higher kinetic energy dissipation when the consequently, standoff distance was increased to 8 mm (Fig.6.c) and 10 mm

(Fig.6.d). At higher kinetic energy conditions dissipated heat causes melting of metals to result in the formation of molten zones as reported by Saravanan and Raghukandan [14] which reduces the tensile strength. The increase in standoff.distance allows the flyer plate to reach its terminal velocity and results in, higher collision velocity and enhanced plastic deformation.

Due to the rapidity of the process, the unescaped jet manifests into a trapped jet as shown in Fig.6.d. The microstructure of Al-Cu explosive clad for a loading ratio, R of 1.0, standoff distance, S -6 mm and preset angle, A-6^o (Fig.6.e) reveals a smooth wavy interface, devoid of intermetallic compounds and results in higher tensile strength [16]. The microstructures highlighted the effect of process parameters viz., loading ratio, preset angle and standoff distance on the nature of Al-Cu explosive clad interface and thereby dictating the tensile strength.

Table 6. Experimental and predicted results

Sl. No	Tensile strength (T) (MPa)		
	Experimental	Predicated	Error (%)
1	84	83.86	0.16
2	85	85.52	1.77
3	89	89.17	0.20
4	77	74.02	3.88
5	46	76.68	0.89
6	85	85.34	0.40
7	63	64.18	1.87
8	71	72.84	2.55
9	78	75.50	3.21



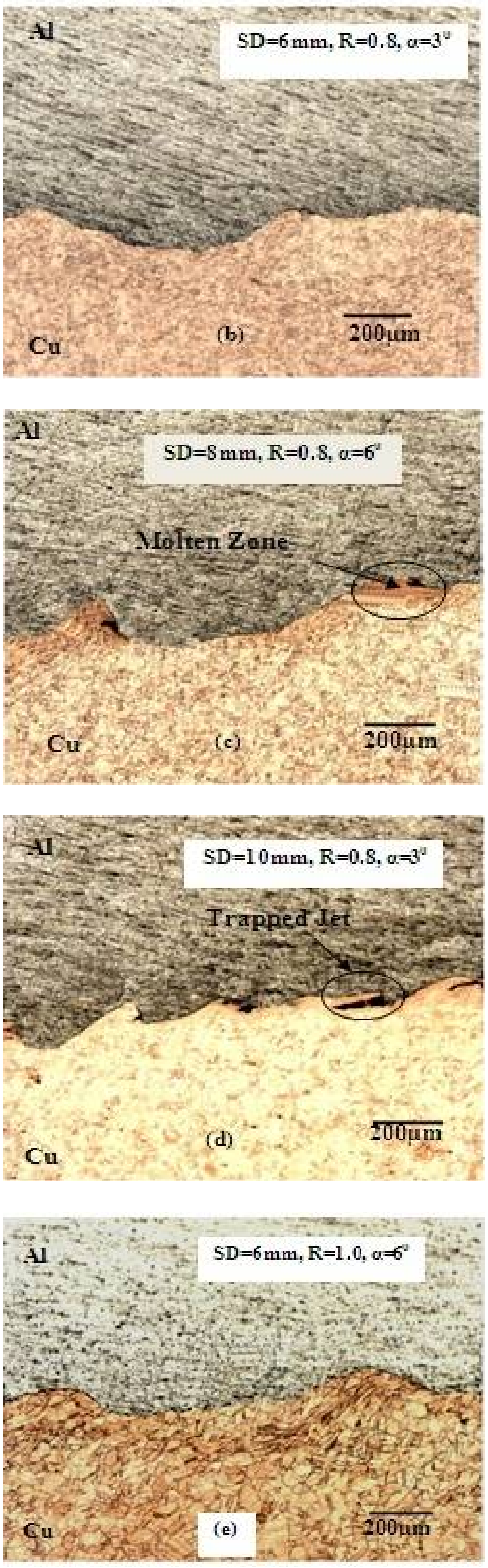


Fig.6. Microstructure of Al-Cu explosive clads

6. Conformation Test

The confirmation test was the final step in verifying the results drawn based on Taguchi's design approach. The confirmation experimental condition with optimum parameters and the response (tensile strength) is shown in Table 7. The predicted response of the mathematical model is in good agreement with the experimental results and the percentage of error is within five.

Table 7. Optimum parameters and the response

Standoff Distance (S) (mm)	**Loading Ratio (R)**	**Preset Angle (A) (^{0})**	**Tensile Strength (MPa)**			**Error (%)**	
			Predicted		**Experimental**	**Taguchi Model**	**Regression Analysis**
			Taguchi model	**Regression Analysis**			
6	1.0	3	93	91.18	90	3.22	1.96

7. Conclusions

1. The tensile strength of Al-Cu explosive clad can be predicted by the developed statistical model.
2. The optimum level of tensile strength for a 95% interval is predicted.
3. The process parameters standoff distance (S) and loading ratio (R) are significantly influencing the Ram tensile strength of the Al-Cu explosive clad.
4. The process parameter standoff distance has most dominant effect (69.8%) on the tensile strength followed by loading ratio (27.8%), whereas the contribution of preset angle (7.8%) is not that severe.
5. The nature of interface is dictated by the kinetic energy dissipated at the collision interface.

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