Journal of Manufacturing Engineering, June, 2016, Vol. 11, Issue. 2, pp 107-112

# OPTIMIZATION OF PROCESS PARAMETERS IN MULTILAYER EXPLOSIVE CLADDING USING TAGUCHI METHOD

***Wilson Dhileep Kumar C[1], Saravanan S[1] and Raghukandan K[2]**

[1] Department of Mechanical Engineering, Annamalai University, Tamilnadu, India.
[2] Department of Manufacturing Engineering, Annamalai University, Tamilnadu, India.

## ABSTRACT

In explosive cladding, an intense deformation resulting from high pressure and temperature emanating from a chemical explosive pack is used to join similar and dissimilar metals. The judicial selection of process parameters viz., explosive loading ratio, interlayer and preset angle is vital in achieving higher clad strength as the process is very rapid. Experiments were conducted based on three factor-three level L9 Taguchi design, to establish the significant process parameters and their optimum levels to obtain higher tensile strength in Aluminum-Stainless steel explosive clads using S/N ratio analysis. A mathematical model was developed to predict the tensile strength of clads using ANOVA. The influence of interfacial morphology on tensile strength of Al-SS304 explosive clads was reported with microstructural analysis. The proposed model can be effectively used to predict the tensile strength of Al-SS304 clads at 95% confidence level.

**Keywords:** *Explosive cladding, Dissimilar metal, Optimization, Interlayer, Microstructure and Tensile strength*

## 1. Introduction

Explosive cladding, a solid state metal joining technique, used to craft a metallurgical bond between two similar or dissimilar metals by a high velocity oblique impact, aided by the controlled detonation of an explosive charge [1]. Explosive cladding (Fig. 1) is a viable method to clad metals that cannot be cladded by conventional methods, viz., titanium-steel, aluminum-steel and aluminum-copper. Aluminum-stainless steel is a popular bimetallic combination employed as transition joints in cryogenic pressure vessels, cryogenic liquid transport vehicles and as hull materials for ship building as they exhibit good corrosion resistance and shock bearing capacity [2]. The tensile strength of Al-SS304 explosive clad ensures the ability to withstand tensile loads without failure when structural components are welded to clad surface in cryogenic applications. As explosive cladding process is very rapid (<50μs), the quality of clad strongly depends on judicial selection of the process parameters, viz., explosive loading ratio, preset angle, standoff distance, interlayer, surface finish, detonation energy and detonation velocity of the explosive [3]. Saravanan et al. [4] focused on the effect of process parameters on interface characteristics of Ti-SS composites whereas Raghukandan [5] developed a mathematical model for predicting the strength of Cu-Low carbon steel explosive clad. Manikandan et al. [6] showed that employing an interlayer is beneficial to control the formation of intermetallics at the interface.

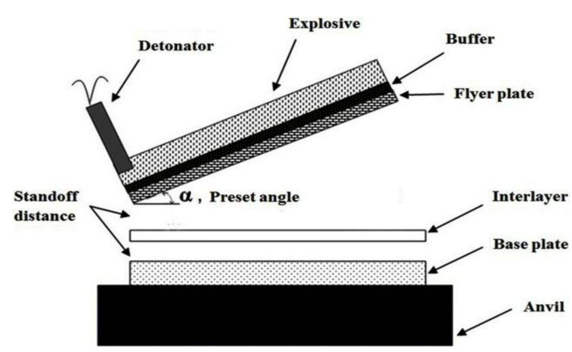



**Fig. 1 Inclined explosive cladding setup with interlayer**

Though statistical techniques are applied in explosive cladding, the study on mathematical modeling in multilayer explosive cladding is limited and is attempted herein. As the number of parameters involved in explosive cladding is more, studying the influence of

**Corresponding Author - E- mail: wilsonapme@gmail.com*

all parameters on the clad strength is time consuming and tedious. In this study, optimization of the process parameters viz., loading ratio, number of interlayer and preset angle is carried out employing Taguchi L9 orthogonal array using signal to noise (S/N) ratio analysis in achieving higher tensile strength is attempted. In addition, a mathematical model is developed to estimate the tensile strength (response) of Al-SS304 explosive clad using analysis of variance (ANOVA) technique which improves the quality of design and extending the range of applications.

## 2. Experimentation

### 2.1 Design of experiment and working range of process parameters

In order to ease the optimization process by limiting the number of experiments, a design of experiment based on the Taguchi L9 orthogonal array was attempted. Taguchi method is a powerful tool for improving productivity during research and development to produce high quality products at low cost. A three-factor, three-level design with 9 trials is selected and the experiments were conducted as per the standard orthogonal array. The nature and strength characteristics of Al-SS304 explosive clad primarily depend on limiting conditions of the process parameters. With the aid of earlier investigations [7, 8] trial experiments were conducted with and without interlayer to identify the ranges of parameters for successful clads. The working range of process parameters were determined for explosive cladding of Al-SS304 and are tabulated in Table 1.

### 2.2 Experimental procedure

Aluminum (120 mm × 50 mm × 3 mm) and stainless steel 304 (120 mm × 50 mm × 6 mm) were employed as flyer and base plates respectively. Aluminum alloy 5251 (120 mm × 50 mm × 0.3 mm) interlayer was employed between the parent plates. The mating plates were positioned at a distance of 5 mm to the adjacent plate. The chemical composition and mechanical properties of the mating plates are given in Table 2 and Table 3 respectively.

All the plates were polished both mechanically and chemically to obtain a clean surface before cladding. Sun 90 explosive (density, $\rho$ = 1.2 gm/cm$^3$, detonation velocity, $V_d$ = 4000 m/s) was packed above the flyer plate and the detonator was positioned on one corner of the flyer plate. Nine experiments were conducted as per the standard orthogonal array. Tensile tests were carried out on Al-SS304 clads according to ASTM E8 standard on the UNITEK-94100 universal testing machine at a crosshead speed of 10 mm/min. The failed specimen after tensile test is shown in Fig. 2. Interfacial microstructure and fractographic studies on Al-SS304 explosive clads were carried out following standard metallurgical procedures.

**Table 1. Process parameters and their levels**

| Parameters | Unit | Notation | Level | | |
|---|---|---|---|---|---|
| | | | Low (-1) | Middle (0) | High (+1) |
| Explosive loading ratio | … | R | 0.7 | 0.9 | 1.1 |
| No. of interlayer | … | I | 0 | 1 | 2 |
| Preset angle | degree | A | 5 | 10 | 15 |

**Table 2. Chemical composition (wt-%) of participant**

| Elements | Cr | Ni | C | Si | Al | Cu | Fe | Mg |
|---|---|---|---|---|---|---|---|---|
| Al (flyer) | … | … | … | 0.1 | Bal. | 0.03 | 0.48 | 0.017 |
| Al 5251 (interlayer) | 0.15 | … | … | 0.4 | Bal. | 0.15 | 0.5 | 1.98 |
| SS304 (base) | 18.9 | 8.4 | 0.015 | 0.48 | … | 0.043 | Bal. | … |

**Table 3. Mechanical properties of participant metals**

| Material | Vickers Hardness ($H_V$) | Ultimate tensile strength (MPa) |
|---|---|---|
| Al (flyer) | 54 | 270 |
| Al 5251 (interlayer) | 50 | 230 |
| SS 304(base) | 234 | 505 |

## 3. Results and Discussion

### 3.1 Tensile test

Tensile loads are applied to Al-SS304 explosive clads until failure and the results are given in Table 4.

**Fig. 2 Fractured specimen after tensile test**

The tensile strength of the explosive clads are higher than aluminum flyer (weaker metal) for all conditions and concurs with the reports of Xia et al. [9] and Acarer [10]. The maximum and minimum tensile strengths (362 MPa and 272 MPa) were obtained for experiment-5 (R-0.9, I-1, A-15o) and experiment-7 (R-1.1, I-0, A-15o) respectively. The lower strength is attributed by the formation of detrimental intermetallic compounds (shown in section 3.4) due to additional kinetic energy dissipation. From Table 4, it is observed that tensile strength of explosive clad increases with preset angle, A as reported by Raghukandan [7]. The average tensile strength is maximum for clads fabricated at a loading ratio (R) of 0.9 and minimum for clads without any interlayer (I=0).

### 3.2 Analysis of S/N ratio

The signal to noise (S/N) ratio analysis is applied for determining the optimum process parameters for obtaining higher tensile strength. The term ‘signal’ and ‘noise’ represent the desirable and undesirable value for the output characteristics respectively. In Taguchi’s approach there are three types of performance characteristics to analyze the S/N ratio viz., lower is better (LB), the nominal is best (NB) and the higher is better (HB). In this study, higher the better (HB) is applied as higher tensile strength is expected. S/N ratio is determined for higher the better using equation [11]

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

where $y_i$ represents the response for i-th experiment and n represents the total number of experiments.

The calculated S/N ratio values are given in Table 4. In order to find the optimum levels of parameters (R, I and A), the main effect plot is plotted (Fig. 3) by using S/N responses for strength

**Table 4. Experimental conditions and results**

| Run | Explosive loading ratio, R | No. of interlayer, I | Angle of inclination, A (degree) | Tensile Strength, TS (MPa) | S/N ratio |
|---|---|---|---|---|---|
| 1 | 0.7 | 0 | 5 | 279 | 48.91 |
| 2 | 0.7 | 1 | 10 | 332 | 50.42 |
| 3 | 0.7 | 2 | 15 | 295 | 49.54 |
| 4 | 0.9 | 0 | 10 | 305 | 49.69 |
| 5 | 0.9 | 1 | 15 | 362 | 51.25 |
| 6 | 0.9 | 2 | 5 | 310 | 49.83 |
| 7 | 1.1 | 0 | 15 | 272 | 48.69 |
| 8 | 1.1 | 1 | 5 | 320 | 50.13 |
| 9 | 1.1 | 2 | 10 | 293 | 49.33 |

. The optimal level of the parameters holds higher S/N value. The optimal factor levels for the strength were obtained at level 2 of R (0.9), I (1), and A (10°). The S/N values and mean response for each level of parameters is calculated and given in Table 5.

Delta (Δ) values for each factor (Table 5) define the difference between maximum and minimum values of S/N ratio and mean response across factor levels. From the highest Δ value in Table 5 and the main effect plot shown in Fig. 3, it is understood that interlayer (I) and loading ratio (R) contribute more than the angle of inclination (A) for obtaining higher tensile strength.

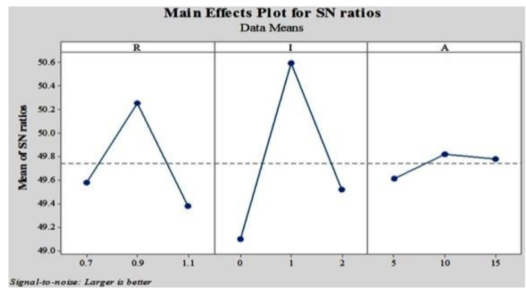



**Fig. 3 Main effects plot for S/N ratios of tensile strength**

**Table 5. S/N ratio and means for tensile strength by factor levels**

| Level | S/N ratio | | | Means | | |
|---|---|---|---|---|---|---|
| | R | I | A | R | I | A |
| 1 | 49.58 | 49.10 | 49.61 | 302.0 | 285.3 | 303.0 |
| 2 | 50.23 | 50.57 | 49.82 | 325.7 | 338.0 | 310.0 |
| 3 | 49.38 | 49.52 | 49.75 | 295.0 | 299.3 | 309.7 |
| Δ | 0.85 | 1.47 | 0.20 | 30.7 | 52.7 | 7.0 |
| Rank | 2 | 1 | 3 | 2 | 1 | 3 |

### 3.3 Mathematical model and ANOVA

Automation of explosive cladding is difficult, and there is a need for comprehensive model to determine the explosive cladding parameters for strong and high quality metallurgical bonds [12]. Hence, a mathematical model is developed to predict the tensile strength of Al-SS304 explosive clad with interlayer. In the model, tensile strength (TS) is treated as a function of process parameters viz., loading ratio, R, number of interlayer, I and preset angle, A in the form:

$$TS = f\ (R, I, A) \tag{2}$$

The general polynomial second order equation to express the response Y is given by [13]

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i,j=1}^{k} b_{ij} x_i x_j + \sum_{i=1}^{k} b_{ii} x_i^2 + \ldots \tag{3}$$

where the polynomial coefficients b0, bi, bii, and bij represent the average of responses, linear, quadratic effects of xi and the interaction effects between xi and xj respectively. For the three process parameters, the selected polynomial could be expressed as

$$TS = b_0 + b_1(R) + b_2(I) + b_3(A) + b_{12}(R \cdot I) + b_{13}(R \cdot A) + b_{23}(I \cdot A) + b_{11}R^2 + b_{22}I^2 + b_{33}A^2 \quad (4)$$

The value of the coefficients was calculated using the following expressions

$$b_0 = 0.165385 \sum Y - 0.057692 \sum (X_{ii} Y) \quad (5)$$

$$b_i = 0.075 \sum (X_i Y) \quad (6)$$

$$b_{ii} = 0.070312 \sum \left(X_{ii} Y\right) + 0.005409 \sum \sum \left(X_{ii} Y\right) - 0.057692 \sum Y \quad (7)$$

$$b_{ij} = 0.125 \sum (X_{ii} Y) \quad (8)$$

The analysis of variance (ANOVA) was implemented to examine the significance of coefficients and the fitness of the mathematical model. All the coefficients were tested for their significance at 95% confidence level applying Fisher's F-test using MINITAB® 17 software package. The results in Table 6 show F and P values of the regression model and the factors. The F value of the model and the factors are above 18.51 and their corresponding probability is less than 0.05 which imply that the model, the first order parameters (R, I and A), the second order parameters (R2 and I2) and the interaction parameters (R*I) are significant. After finding the significant coefficients, the empirical relationship was developed using these coefficients and the final mathematical model to estimate tensile strength of explosive clad is expressed in the following form as

| Source | Degrees of freedom | Adj. SS | Adj.MS | F- value | P-value |
|---|---|---|---|---|---|
| Regression | 6 | 6171.1 | 1028.5 | 289.27 | 0.003 |
| R | 1 | 73.50 | 73.50 | 20.67 | 0.045 |
| I | 1 | 294.00 | 294.00 | 82.69 | 0.012 |
| A | 1 | 150.42 | 150.42 | 42.30 | 0.023 |
| R*R | 1 | 1476.1 | 1476.1 | 415.14 | 0.002 |
| I*I | 1 | 4170.8 | 4170.8 | 1173.1 | 0.001 |
| R*I | 1 | 90.00 | 90.00 | 25.31 | 0.037 |
| Error | 2 | 7.11 | 3.56 | | |
| Total | 8 | 6178.2 | | | |

Critical values of F-ratio at 95% confidence level:
F (0.05, 1, 2) = 18.51
R-sq - 98.21 %   R-sq(adj) - 98.13%   R-sq(pred) - 95.84 %

$$TS = 356.11 - 3.5(R) + 7(I) + 6.33(A) - 27.17(R^2) - 45.67(I^2) + 6(R \cdot I) \quad (9)$$

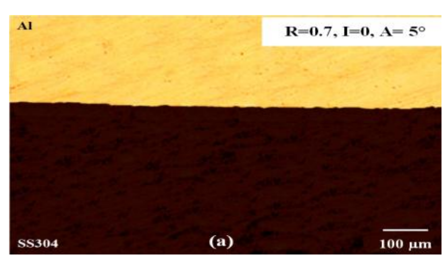
The R2 and adj. R2 values (over 98%) indicate that the regression model provides a good correlation between the process parameters and response. The predicted $R^2$ value (above 95%) reveals that the developed model predicts the response well.

### 3.4 Microstructural characterization

The strength of an explosive clad primarily depends on the nature of interface examined through microstructural analysis [14]. Fig. 4 illustrates the microstructure of the Al-SS304 explosive clads fabricated with and without interlayer captured by optical microscope.

For the explosive loading ratio R=0.7, a straight interface was obtained in the conventional bilayer cladding (Fig. 4a) and while keeping interlayer waviness is observed at Al-Al interface (Fig. 4b).

When the densities of cladding materials are similar then high pressure generated at the collision point makes them to behave like fluid resulting in wavy interface. When increasing loading ratio from 0.7 to 0.9 continuous molten intermetallic layer is seen at Al-SS304 interface in bilayer cladding (Fig. 4c) as reported by Han et al [15]. Increasing the explosive mass in bilayer cladding, the flyer velocity increases which in turn increases the kinetic energy. During collision, in addition to the kinetic energy spent on plastic deformation the excess kinetic energy is converted and dissipated in form of heat at the interface which rises the interface temperature locally to result in formation of molten layer. When an interlayer is employed, wavy interface was obtained on similar material side whereas a straight interface, devoid of the intermetallic compounds was obtained on the dissimilar side (Fig. 4d).



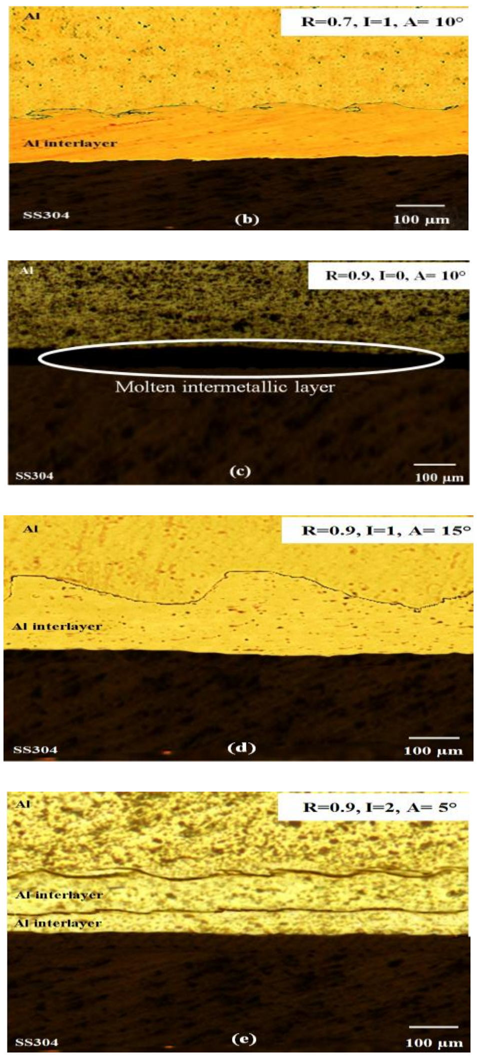



**Fig.4 Optical microstructure of explosive clads (a) Al-SS304 (b) Al-Al-SS304 (c) Al-SS304 interface with molten intermetallic layer (d) Al-Al-SS304 (e) Al-Al-Al-SS304**

The microstructure observed by optical microscopy for three-layer clad (Al-Al-SS304) across the interface shows an intense plastic deformation and the wave pattern indicates material flow is more pronounced on the similar material side. During the collision of flyer plate with the interlayer, the kinetic energy of the flyer plate is partly transformed to thermal energy. This enables the interlayer and flyer plate to plastically deform along the surface. The kinetic energy dissipated at the interface between flyer plate and interlayer results in wavy interface due to plastic deformation with heat transfer between materials of higher thermal expansion coefficient. In the region between interlayer and base plate, due to density difference exist between materials the kinetic energy available for plastic deformation is insufficient to modify the microstructure to form any vortices resulting in a straight interface. Saravanan and Raghukandan [16] opined that interlayer significantly enhances the kinetic energy utilization and suppresses the formation of detrimental intermetallic compounds at the interface. When the second interlayer is introduced, kinetic energy of the flyer plate is further reduced to result in small waves at the interfaces (Fig. 4e). The wave amplitude is higher at the first interface and tends to decrease at the second and third interface respectively. The maximum tensile strength (362 MPa) is obtained for clad with single interlayer (Fig. 4d) showing peaks in wave amplitude. Increase in wave amplitude increases the inter-penetration between the metals (weld area) results in higher tensile strength as reported by Mousavi et al. [17]. The minimum tensile strength of 272 MPa is exhibited by the clad with molten intermetallic layer at the interface (Fig. 4c) and is concurrent with Tricarico et al. [18] reported that the intermetallics formed in explosive clads decreases the strength of clads. For all the experiments carried out with interlayer in this study, no significant traces of molten layer or intermetallics were identified at the interface and the explosive clads exhibited good tensile strength. From the microscopic examinations, it can be inferred that the microstructural changes at the interface are driven by the plastic deformation generated by the kinetic energy loss and the interface characteristics have significant influence on tensile strength properties of Al-SS304 explosive clads.

### 3.5 Confirmation experiment

Using the optimal design parameters identified from the S/N ratio analysis confirmation experiment was conducted, to substantiate the optimum process parameters and to validate the developed model. Three experiments were conducted for optimum values (R=0.9, I=1, A=10º) and the average tensile strength is given in Table 7. The predicted responses are in good agreement with the obtained results and the calculated error is within 2%.

**Table 7. Results of confirmation experiment**

| Optimum values | Tensile Strength (MPa) | | | Error (%) |
|---|---|---|---|---|
| | Fit (from developed model | 95% prediction interval | Experimental value (average) | |
| R= 0.9<br>I=1<br>A=10º | 356.11 | 345.99<br>to<br>366.23 | 352.33 | 1.06 |

## 4. Conclusions

1. No. of Interlayer (I) and loading ratio (R) significantly contributes to the tensile strength of Al-SS304 explosive clads.
2. Single interlayer is beneficial than multiple interlayer for enhancing clad properties.
3. Interfacial microstructure is characterized by kinetic energy lost at the clad interface.
4. The developed mathematical model can be used to evaluate the tensile strength characteristic of the explosive clads.
5. Taguchi method is very effective in optimizing process parameters for achieving high tensile strength.

## References


1. *Hosein Bina M and Dehghani F S M (2013), "Effect of heat treatment on bonding interface in explosive welded copper/stainless steel", Mater. Des, Vol. 45, 504-509.*

2. *Aceves S M Espinosa-Loza F Elmer J W and Huber R (2015) , "Comparison of Cu, Ti and Ta interlayer explosively fabricated aluminum to stainless steel transition joints for cryogenic pressurized hydrogen storage", Int J Hydrog Energy, Vol. 40(3), 1490-1503.*

3. *De Rosset W S (2006), "Analysis of explosive bonding parameters", Mater. Manuf. Process, Vol. 21, 634-638.*

4. *Saravanan S Raghukandan K and Tamilchelvan P (2015), "Parametric Studies on Explosive Cladded Titanium-Stainless steel Composites", Journal of Manufacturing Engineering, Vol. 10(3), 161-165.*

5. *Raghukandan K (2003), "Analysis of the explosive cladding of Cu-low carbon steel plates", J. Mater. Process. Technol, Vol. 139, 573-577.*

6. *Manikandan P Hokamoto K Fujita M Raghukandan K and Tomoshige R (2008), "Control of energetic conditions by employing interlayer of different thickness for explosive welding of titanium/304 stainless steel", J. Mater. Process. Technol, Vol. 195, 232-240.*

7. *Raghukandan K Hokamoto K and Manikandan P (2004), "Optimization of process parameters in explosive cladding of mild steel and aluminum", Met. Mater. Int, Vol. 10, 193-197.*

8. *Tamilchelvan P Raghukandan K Meikandan N and Sivakumar K (2008), "Micro structural studies on explosively clad Cu/SS, Br/SS and Al/SS plates", Mater. Sci. Forum, Vol. 566, 279-284.*

9. *Xia H B Wang S G and Ben HF (2014), "Microstructure and mechanical properties of Ti-Al explosive cladding", Mater. Des, Vol. 56, 1014-1019.*

10. *Acarer M (2012), "Electrical, corrosion, and mechanical properties of aluminum-copper joints produced by explosive welding", J. Mater. Eng. Perform, Vol. 21, 2375-2379.*

11. *Shojaeefard M H Akbari M Khalkhali A Asadi P and Parivar A H (2014), "Optimization of microstructural and mechanical properties of friction stir welding using the cellular automaton and Taguchi method", Mater. Des, Vol. 64, 660-666.*

12. *Ashani J Z and Bagheri S M (2009), "Explosive scarf welding of aluminum to copper plates and their interface properties", Materialwiss., Werkst, Vol. 40, 690-698.*

13. *Palani P K and Murugan N (2006), "Development of mathematical models for prediction of weld bead geometry in cladding by flux cored arc welding", Int. J. Manuf. Technol, Vol. 30, 669-676.*

14. *Mallesham P Gokhale A A and Murti V S R (2003), "Nature of the interface between AA7072 alloy explosively clad to AA8090 aluminum alloy", J. Mater. Sci, Vol. 38, 1869-1873.*

15. *Han J H Ahn J P and Shin M C (2003), "Effect of interlayer thickness on shear deformation behavior of AA5083 aluminum alloy/SS 41 plates manufactured by explosive welding", J. Mater. Sci, Vol. 38, 13-18.*

16. *Saravanan S and Raghukandan K (2013), "Influence of interlayer in explosive cladding of dissimilar metals", Mater. Manuf. Process, Vol. 28, 589-594.*

17. *Akbari Mousavi S A A Al-Hassani S T S and Atkins A G (2008), "Bond strength of explosively welded specimens", Mater. Des, Vol. 29, 1334-1352.*

18. *Tricarico L Spina Sorgente D and Brandizzi M (2009), "Effects of heat treatments on mechanical properties of Fe/Al explosion-welded structural transition joints", Mater. Des, Vol. 30(7), 2693-2700.*