Journal of Manufacturing Engineering, September, 2014, Vol. 9, Issue. 3, pp 190-196

DEVELOPING AN EMPIRICAL RELATIONSHIP TO PREDICT BONDING STRENGTH OF FRICTION SURFACED MATERIALS

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ABSTRACT

Friction surfacing was attempted with an Aluminum rod on a Mild steel Substrate. In this paper Empirical relationship were developed using three factors fine levels. Factorial technique to predict the coating bond strength. Design of experiments concepts has been used to optimize the number of experimental conditions. These factorial techniques are used to reduce the cost and time involved, as well as to obtain the information about the direct effect on the response parameters. This process of friction surfacing is mainly controlled by parameters like Rotational speed, traverse speed and Axial Force. The experiment has been conducted by varying process parameters as per the design matrix and the resultant bonding strength has been calculated. The effect of these parameters on the factor of bond strength of the coatings have been measured and optimized for various applications of Friction surfacing using RSM technique. Using RSM technique, we optimize for the optimal values of the Process parameters of Friction surfacing to get maximum bonding strength for the frictionally surfaced materials for their applications.

Keywords: *Friction surfacing, bonding strength, factorial technique and RSM technique.*

1. Introduction

Friction surfacing is a solid phase process which produces coatings with hot forged microstructures that are typically fine homogeneous and soundly bonded to the substrate. The process involves a rotating consumable rod of the coating material onto a substrate through the friction at the rubbing interface, generates sufficient heat to plastically deform the end of the coating rod (Mechtrode TM). By moving the substrate across the face of the rotating rod, a layer of (Mechtrode TM) material is deposited. The coating is extremely regular and flat, without the familiar meniscus section profile experienced with fusion welding methods. The thickness of the coated layer is typically between 0.5 and 3 mm depending on Mechtrode diameter and material. The process itself is environmentally clean, with no fumes, spatter or high intensity light emissions as in laser-based coating methods.

It is also energy efficient because the heat is generated and used exactly where it is needed. The process is used to create coatings with desired surface properties such as wear resistant coatings [1, 2, 3,4and5].

Friction surfacing involves a number of process parameters which directly affect the Coating quality (i.e. bonding strength). During the coating process, the applied layer of metal reaches a temperature near the melting point whilst simultaneously undergoing plastic deformation. The coating is thus the product of a hot forging action, as opposed to the casting mechanism inherent in welding and spraying processes. This important difference means that many of the defects commonly associated with these techniques are avoided.

A valid mathematical or analytical description of the process should successfully combine the significant parameters. The existing friction surfacing models are based mainly on empirical equations or on experiments performed under a number of theoretical considerations. However, they do not account for the dynamics of the friction surfacing process parameters. The behavior of these models has neither been analyzed for cases when the friction surfacing model parameters vary as a response to different external influences, nor for measurement and estimation errors. Hence, the models have not been validated and their value for direct process monitoring and control is very limited[6].

The main objectives of the investigations are to studying the effect of Friction surfacing process parameters on metallurgical properties of bonding strength. The work described in this paper is concerned with the use of both mathematical and statistical approaches to analyze the process parameters like axial force, Rotational speed and Traverse speed.

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2. Plan of Investigation

2.1 Identifying the important process parameters

From the literature (5) and the previous work done in our laboratory, the predominant factors which are having greater influence on bonding strength of friction surfaced aluminium alloys were identified. They are: (i) Rotational speed (ii) traverse speed and (iii) Axial (downward) force. Trial experiments were conducted to determine the working range of the above factors. Feasible limits of the parameters were chosen in such a way that the friction surfaced specimens should be free from any visible external defects. The important factors that are influencing the bonding strength properties of friction surfaced materials and their working range for AA1100 aluminium alloys are presented in Table 1.

Table 1: Mechanical Properties

Sl. No	Material	Yield strength (Mpa)	Tensile strength (Mpa)	% of elongation	Hardness (HV)
1	Base metal (Mild Steel)	309	426	45	175
2	Consumable (AA1100 Aluminum Alloy)	197	211	26	84

2.2 Finding the Working Limits of the Parameters

A large number of trial runs were carried out using aluminum alloy (22 mm Ø) to be coated on mild steel substrate (150 mm x 100 mm x 6 mm) to find out the feasible working limits of Friction surfacing process parameters. Chemical composition of the base metal and consumable is presented in Table 2. Trial runs were carried out by varying one of the factors while keeping the rest of them at constant values.

2.3 Developing the Experimental Design Matrix

Due to wide range of factors, it was decided to use three factors, five levels, central composite design matrix to optimise the experimental conditions. Table 2 shows the 20 sets of coded conditions used to form the design matrix. First 8 experimental conditions are derived from full factorial experimental design matrix (2^3= 16). All the variables at the intermediate (0) level constitute the center points while the combinations of each process variable at either its lowest (- 2) or its highest (+ 2) with the other three variables of the intermediate levels constitute the star points. Thus the 20 experimental conditions allowed the estimation of the linear, quadratic and two-way interactive effects of the variables on the bonding strength of friction surfaced specimens.

Table 2: Important factors and their level

Sl.No	Factors	Notation	Unit	Levels -2	-1	0	1	2
1	Axial force	F	KN	4	6	8	10	12
2	Rotational speed	N	Rpm	1700	1800	1900	2000	2100
3	Traverse speed	V	Mm/sec	0.37	0.67	1.25	1.76	2.5

The method of designing such matrix is dealt elsewhere (11, 12, and 14). For the convenience of recording and processing experimental data, upper and lower levels of the factors have been coded as +2 and –2 respectively. The coded values of the any intermediate values can be calculated using the following relationship (13).

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

Where,

X_i is the required coded value of a variable X;

X is any value of the variable from X_{min} to X_{max};

X_{min} is the lower level of the variable;

X_{max} is the highest level of the variable.

As prescribed by the design matrix twenty friction surfaced material were fabricated.

2.4. Data evaluation and optimization procedures

The friction surfacing of aluminum coating was performed on mild steel substrate as per the conditions dictated by the design matrix (Table2). Some evaluation of coating characteristics (coating thickness, coating width) can be carried out immediately after completion of a experimental work. Coating thickness, coating width was measured by using optical profile projector (make: Meterz, India)this is useful when experimental optimization is being carried out. Evaluating coating appearance gives guidelines for finding the area of interest for more precise investigation.[7,8]

From the investigation, to determine the optimum conditions for coating quality and to enable a more detailed study of the coating process, the optimized friction surfacing parameters of the successful friction surfaced samples are produced; the sample specimens are shown in Fig.2

2.5 conducting the experiments and recording the responses

Bonding Strength is the term defined in Friction surfacing as the strength of the bond between the Substrate (Mild steel) and Coating material (Aluminum) which is denoted in Mpa. The comparative strength of the bond is currently measured using Ram Tensile Test, in which a hole was drilled from the back of the deposit, and to applied load through punch, while measuring the displacement and stress, when the coating was detached from the substrate a value was recorded. The Equipment used for testing the bonding strength of the frictionally surfaced material is universal testing machine (UTM). The photograph of the UTM is given in fig. 1.

Fig. 1 Universal testing machine

A 25 mm length was cut from the substrate deposit using EDM. The hole diameter was 4mm and positioned in the centre of the deposit cut-off. The specimens before Ram tensile test (front side and back side) were shown in fig (2) and fig (3). The width of the deposit was measured; it was possible to calculate the area on which the load was applied. Currently, more sensitive and accurate strength tests were being developed and bond strength was calculated. The friction surfaced specimens after test were shown in fig(4)

Fig. 2 Specimen before Testing

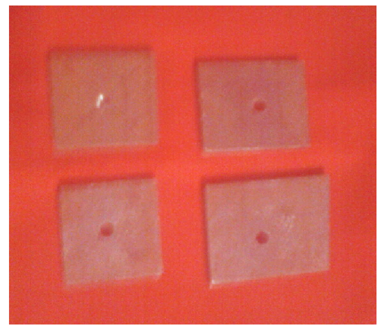


Fig. 3 Specimen before testing (Back side)

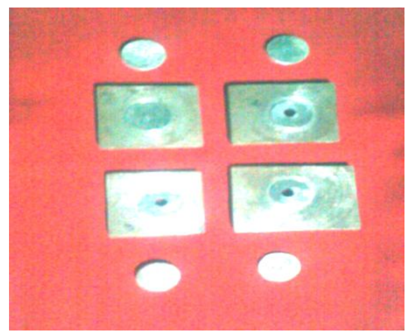


Fig. 4 Ram Tensile test specimens after testing

Table 3: Design Matrix

Axial Force (KN)	Rotational speed (rpm)	Traverse Speed (mm/sec)	Bonding Strength (Mpa)
-1	-1	-1	19
1	-1	-1	34
-1	1	-1	24
1	1	-1	36
-1	-1	1	30
1	-1	1	34
-1	1	1	28
1	1	1	32
-2	0	0	21
-2	0	0	36
0	-2	0	28
0	-2	0	34
0	0	-2	24
0	0	-2	35
0	0	0	36
0	0	0	34
0	0	0	36
0	0	0	36
0	0	0	34
0	0	0	36

3. Developing Empirical Relationships

The response function bond strength of the deposited specimens is a function of rotational speed (N), traverse speed (V) and axial force (F) and it can be expressed as

CBS= f (N, V, F)

The second order polynomial (regression) equation used to represent the response surface 'Y' is given by

$Y = b_0 + \sum bi\ xi + \sum bii\ xi2 + \sum bij\ xi\ xj$

and for three factors, the selected polynomial could be expressed as

CBS=B0+B(F)+B2(N)+B3(V)+B11(F2)
B22(N2)+B33(V2)+B12(F*N)+B13(F*V)+B2 3(N*V)

where bo is the average of responses and B1, B2,….B23 are the co-efficients that depend on respective main and interaction effects of the parameters. The value of the co-efficients has been calculated using the following expressions (14).

$B0 = 0.142857 (\sum Y) – 0.035714 \sum\sum (Xii\ Y)$

$Bi = 0.041667 \sum (Xi\ Y)$

$Bii = 0.03125 \sum (Xii\ Y) + 0.00372 \sum\sum (Xii\ Y) – 0.035714 (\sum Y)$

$Bij = 0.0625 \sum (Xij\ Y)$

All the coefficients were tested for their significance at 90% confidence level applying student's t-test using SPSS statistical software package. After determining the significant coefficients, the final models were developed using only these coefficients and the final mathematical models to predict bonding strength of friction surfaced specimens.

Analysis for variance (ANOVA) test results

Table 3.1: Estimated Regression Coefficients for C8

Term	Coef	SE Coef	T	P
Constant	35.4899	0.6244	56.836	0.000
A	4.4100	0.4143	10.645	0.000
B	0.9585	0.4143	5.214	0.000
A*A	-2.4090	0.4033	-5.973	0.000
B*B	-1.5251	0.4033	-3.782	0.004
C*C	-2.0554	0.4033	-5.097	0.000
A*B	-0.3750	0.5413	-0.693	0.504
A*C	-2.3750	0.5413	-4.388	0.001
B*C	-1.3750	0.5413	-2.540	0.029

S = 1.53103 PRESS = 158.275

R-Sq = 95.94%
R-Sq (pred) = 72.56%
R-Sq(adj) = 92.28%

Table 3.2: Estimated Regression Coefficients for C8 using data in un coded units

Term	Coef
Constant	-712.424
A	18.0508
B	0.634782
C	86.1462
A*A	-0.602249
B*B	-1.52511E-04
C*C	-6.92010
A*B	-0.00187500
A*C	-2.17890
B*C	-0.0252294

3.1 Checking the Adequacy of Model

The adequacy of the model was checked using the analysis of variance (ANOVA) technique. As per the technique, if the calculated value of 'F' ratio for the desired level of confidence (say 99%). Then the model is conducted to the adequacy limit using the developed model for various mechanical and metallurgical properties. The predicted results of different combination are presented in the graphical form. ANOVA test result presented in the Table 4.

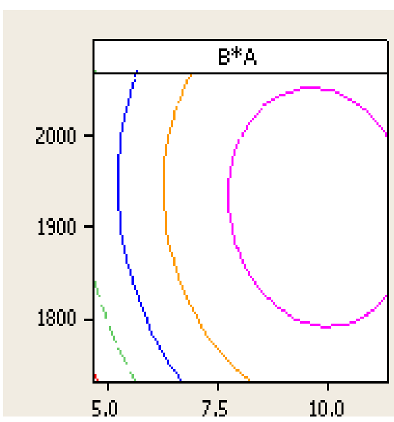
Table 3.3: Analysis of Variance for C8

Source	DF	Seq	SS
Regression	9	553.360	553.360
Linear		3	341.871
0.000			
Square		3	150.114
0.000			
Interaction		3	61.375
0.004			
Residual Error		10	23.440
Lack-of-Fit		5	19.940
0.040			
Pure Error		5	3.500
Total		19	576.800

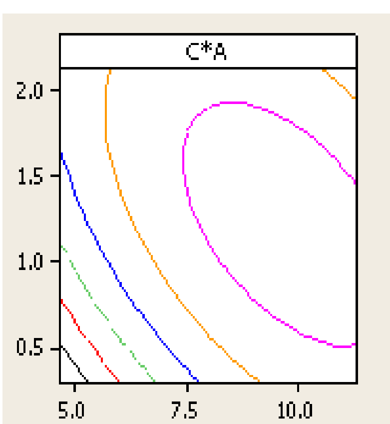
Adj SS	Adj MS	F P
61.484	26.23	0.000
341.871	113.957	48.62
150.114	50.038	21.35
61.375	20.458	8.73
23.440	2.344	
19.940	3.988	5.70
3.500	0.700	

4. Optimising the Parameters

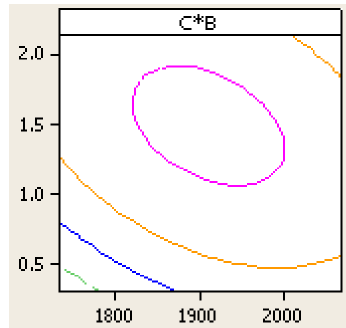
Contour plots show distinctive circular shape indicative of possible independence of factor with response (Figure 5). A contour plot is produced to visually display the region of optimal factor settings. For second order response surface, such a plot can be more complex than the simple series of parallel lines that can occur with first order models. Once the stationary point is found, it is usually necessary to characterize the response surface in the immediate vicinity of the point. Characterization means, identifying whether the stationary point found is a maximum response or minimum response or a saddle point. To classify this, the most straightforward way is to examine through a contour plot. Contour plots play a very important role in the study of the response surface. By generating contour plots using software for response surface analysis, the optimum value is located with reasonable accuracy by characterizing the shape of the surface.



Rotational speed Vs Axial force



Traverse speed Vs Axial force



Traverse speed Vs Rotational speed

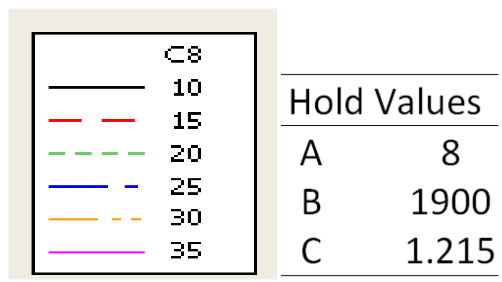
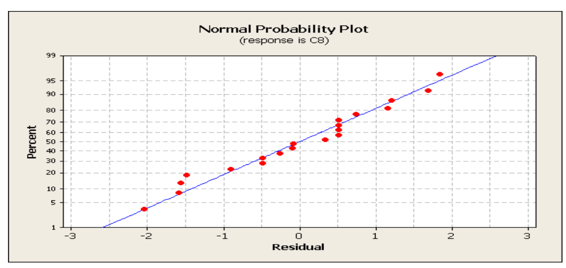


Fig. 5 Contour plots For AA1100 Friction surface deposits on bonding strength



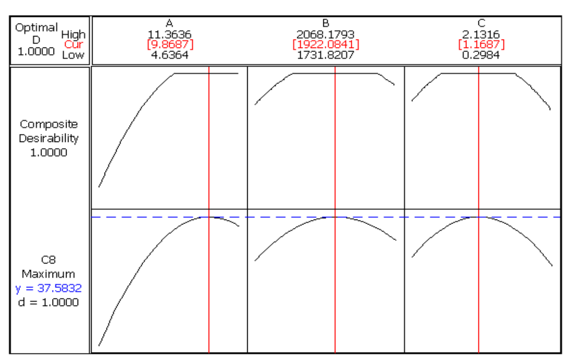


Fig. 6 Response surface Plots

If a contour patterning of circular shaped contours occurs, it tends to suggest independence of factor effects while elliptical contours as may indicate factor interactions. Response surfaces have been developed for both the models, taking two parameters in the middle level and two parameters in the X and Y axis and response in Z axis. The response surfaces clearly reveals the optimal response point. RSM is used to find the optimal set of process parameters that produce a maximum or minimum value of the response.

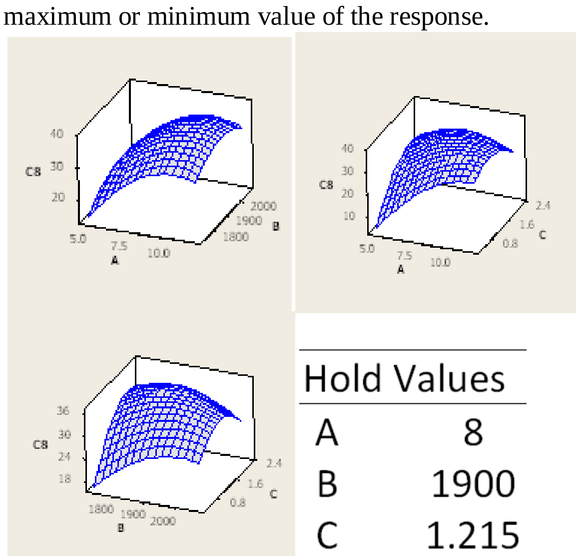


Fig. 7 Bonding Strength Measurement

The adopted experimental approach indicates dependencies between process parameters V, F and N, and coating state variables bond strength of coating (C_{bs}), coating thickness (C_t), coating width (Ct). Fig (7) shows an result of bonding strength measurement carried out by Ram Tensile test, the functional relationships between major parameters and state variables have been obtained. These results from a foundation for reverse process design. On the basis of detailed measurements the following observations were derived: Increasing Axial force increases proportionally the bond strength; increasing traverse speed has a second order relationship to the bond strength; low values of traverse speed (V) make the coating thicker; an increase of coating thickness weakens the bond; high traverse speed reduces the coating thickness, and bonding time, resulting in reduced bond strength; and the traverse speed has its optimum value ,bond quality is also related to input parameters[9,10].

From the optimized results of the graphs, we get results regarding the effect of Process parameters of Friction surfacing process on the Bonding strength. The Friction surfacing was made on the Mild steel plate with Aluminium. The process parameters of the Friction surfacing process is Axial Force, Rotational speed and Traverse speed and their effect on bonding strength has been demonstrated on Table, and this result has been optimized for the best outcome of better Bonding strength of frictionally surfaced material.

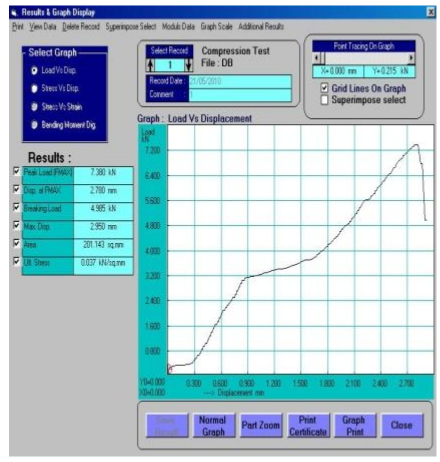


Fig. 8(a) Load Vs Displacement Graphs for Bonding Strength

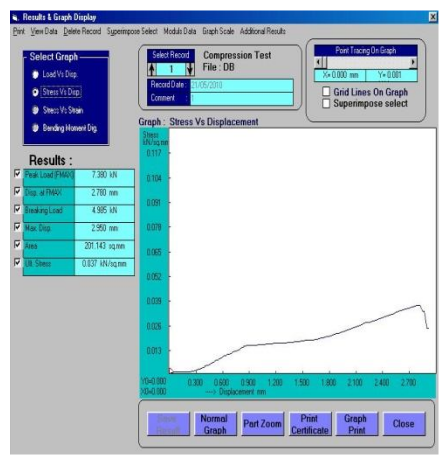


Fig. 8(b) Stress Vs Displacement Graphs for Bonding Strength

The better bonding strength has been calculated for the optimal process parameters and has been given below

Axial Force	–	9.86 KN
Rotational speed	-	1922 RPM
Traverse Speed	-	1.16 mm/sec
Bonding Strength	-	37.5 Mpa

Friction surfacing process parameters were optimized using response surface methodology to attain maximum Bonding strength. The optimum conditions are: axial force 9.86KN, rotational speed 1922rpm and traverse speed 1.166mm/sec. The Maximum bonding strength that can be attained using these parameters is 37.5 Mpa.

5. Conclusions

1. An empirical relationship was developed to predict the bonding strength of friction surfaced aluminum coating with mild steel substrate at 95% confidence level, incorporating friction surfacing process parameters.
2. Bond strength was also related to optimum values of major input parameters.

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