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Optimization of friction stir spot welding parameters on dissimilar joints using response surface methodology

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***Abstract*— Joining of dissimilar materials pose a challenge due to differences in mechanical and chemical properties of the materials. For these types of requirements, solid state joining process like friction welding are used. A variant of linear friction stir welding called as friction stir spot welding process is used for spot joining in lap configurations. In this paper optimization of friction stir spot welding process parameters of dissimilar Aluminium/ Copper joints, such as tool rotational speed, axial plunge depth and dwell time is done using response surface methodology. The effect of the process parameters on strength of the dissimilar joints are ascertained. Optimum parameters for maximum weld strength is obtained.**

Keywords*— *Friction stir spot welding; dissimilar materials; optimization; Response Surface Methodology

I. INTRODUCTION

Response surface methodology (RSM) is a statistical tool used to explore relationships between many explanatory variables and one or more response variables, which was introduced by G. E. P. Box and K. B. Wilson in 1951 [1]. An optimal response is obtained, by using sequentially designed set of experiments [2].

For the purpose of elimination of copper (II) ions from watery solution, the utilization of waste flax meal was explored. A feed-forward neural network with a proper framework, which was properly optimized by using RSM, was applied for appropriate prediction of the bio sorption performance for the effective removal of Cu^{2+} ions by waste flax meal [3].

Using a fully developed three dimensional heat transfer and flow model, the geometric design for double tube heat exchangers with inner corrugated tube was investigated using response surface methodology [4].

Modelling of experimental data of surface roughness of $Co_{28}Cr_6Mo$ medical alloy machined using a completely computer numerically controlled lathe using optimized cutting conditions (spindle speed of circular rotation, feed rate, depth of cut and tool tip radius) were done and evaluated using response surface methodology [5].

Friction stir spot welding (FSSW), a linear variant of friction stir welding (FSW), is a novel method of joining dissimilar materials with different melting, boiling point, density differences etc. [6]. Friction stir spot welding of high-Mn twinning-induced plasticity steel has been studied and its microstructural characteristics and physical aspects were evaluated [7].

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II. EXPERIMENTAL INVESTIGATIONS

A. *Materials and Methods*

For the present investigation, two different dissimilar combination of material were chosen. Alloy plates of Aluminum and Copper were chosen with a thickness of 1.5 mm. The process parameters which determine the output quality of friction stir spot dissimilar joints are

- Tool Penetration Depth in mm
- Tool rotation rate in rpm
- Tool shoulder plunge depth in mm
- Dwell time – Operation duration in seconds
- Tool plunge speed in mm/min
- Axial force of the rotating tool in N

From these three most important process parameters are chosen and listed in Table 1

TABLE 1 - Process parameters of FSSW

S No	Parameters	Notation
1	Tool rotational speed (rpm)	R
2	Dwell time in seconds	T
3	Plunge depth in mm	D

B. *Identification of feasible process parameters*

Initial sets of experiments were conducted by trial and error method and with reference from previous literatures and the feasible limits of the process parameters for proper joining of dissimilar materials are obtained. The lower limit is set below which the material does not weld together and the upper limit is set beyond which there is excess heat generation.

Experiments were conducted to attain the feasible working parameters for the tool rotational speed RS in rpm, Dwell time DT in seconds and Plunge depth PD in millimeters.

For RS, DT and PD the mean values were taken as 950, 6, 1 whereas low and high values were taken as 900, 5, 0.8 and 1000, 7, 1.2 respectively.

A 3 factor three level central composite design is chosen as shown in Table 2.

TABLE 2. 3 factor 3 levels of FSSW

S No	Name	Unit	Level		Alpha	
			Low	High	Low	High
1	R	rpm	-1	1	-1.68	1.68
2	T	sec	-1	1	-1.68	1.68
3	D	mm	-1	1	-1.68	1.68

The total number of runs = 20

No of not center points = 14

No of center points = 6

The response is two

1. Hardness of Al material
2. Hardness of Cu material

The central composite design matrix is given in Table 3

TABLE 3. Design Matrix

S No	Std	Run	R	T	D
1	7	1	-1	1	1
2	16	2	0	0	0
3	9	3	-1.68	0	0
4	3	4	-1	1	-1
5	1	5	-1	-1	-1
6	18	6	0	0	0
7	6	7	1	-1	1
8	4	8	1	1	-1
9	14	9	0	0	1.68
10	20	10	0	0	0
11	2	11	1	-1	-1
12	10	12	1.68	0	0
13	12	13	0	1.68	0
14	19	14	0	0	0
15	13	15	0	0	-1.68
16	11	16	0	-1.68	0
17	15	17	0	0	0
18	17	18	0	0	0
19	8	19	1	1	1
20	5	20	-1	-1	1

The design summary of the response surface study, with initial central composite design, of the quadratic model is given in Table 4. The correlation at 0.068 for Al hardness and at 0.067 for Cu hardness are given in Fig. 1 and Fig. 2.

TABLE 4. Design summary

Study Type	Response Surface		Runs	20							
Initial Design	Central Composite		Blocks	No Blocks							
Design Model	Quadratic										
Factor	Name	Units	Type	Low Actual	High Actual	Low Coded	High Coded	Mean	Std. Dev.		
A	R	rpm	Numeric	-1	1	-1	1	0	0.826343		
B	T	seconds	Numeric	-1	1	-1	1	0	0.826343		
C	D	millimeter	Numeric	-1	1	-1	1	0	0.826343		
Response	Name	Units	Obs	Analysis	Minimum	Maximum	Mean	Std. Dev.	Ratio	Trans	Model
Y1	Al hardness	HV	20	Polynomial	83	105	92.65	6.51364	1.26506	None	No model chosen
Y2	Cu hardness	HV	20	Polynomial	69	93	79.95	6.917189	1.347826	None	No model chosen

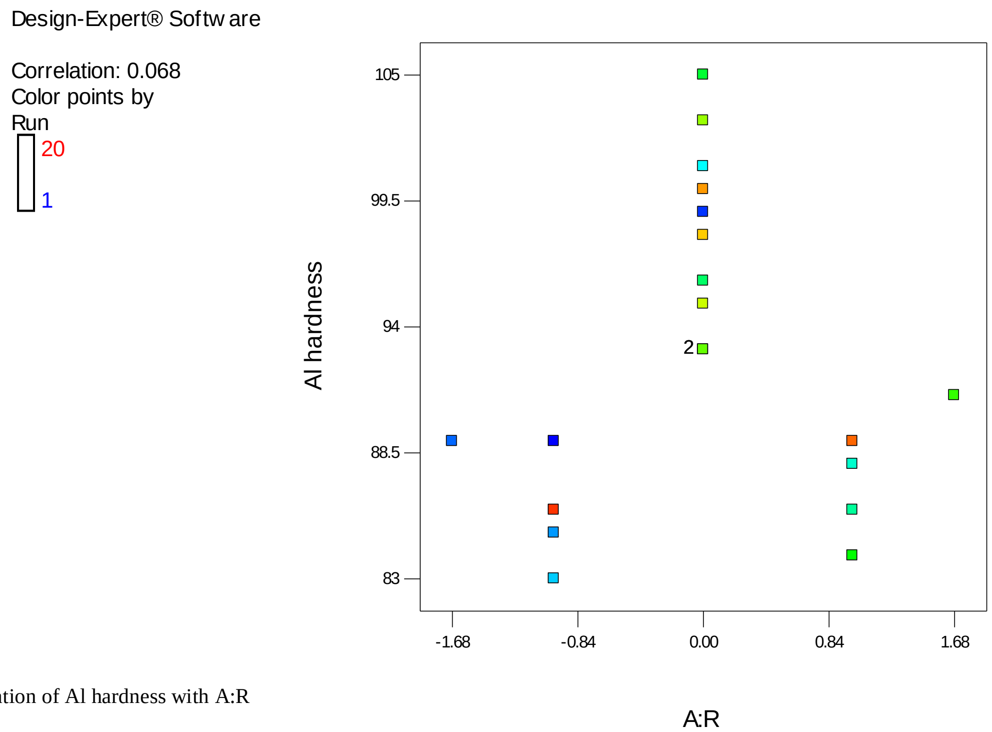

Fig 1. Correlation of Al hardness with A:R

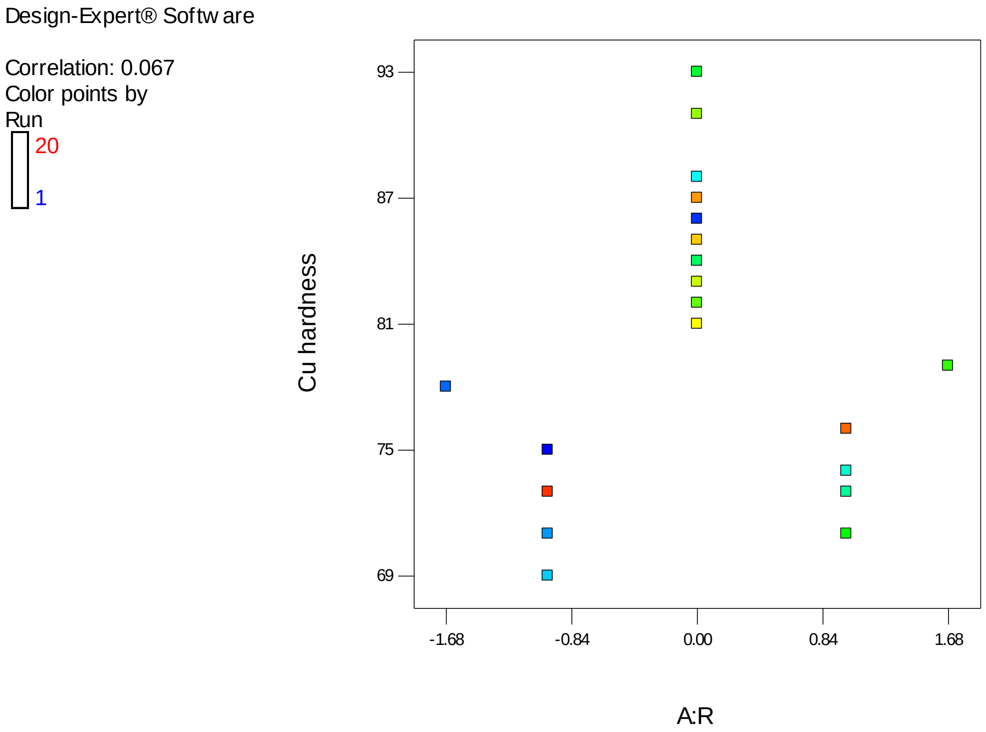

Fig. 2. Correlation of Cu hardness with A:R

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Design Matrix Evaluation for Response Surface Quadratic Model is given in

Degrees of Freedom for Evaluation

Model	9
Residuals	10
Lack 0f Fit	5
Pure Error	5
Corr Total	19

TABLE – 5. Design evaluation response model

Power at 5 % alpha level for effect of						
Term	StdErr**	VIF	Ri-Squared	0.5 Std. Dev.	1 Std. Dev.	2 Std. Dev.
A	0.270598	1	0	13.3 %	38.6 %	91.4 %
B	0.270598	1	0	13.3 %	38.6 %	91.4 %
C	0.270598	1	0	13.3 %	38.6 %	91.4 %
AB	0.353553	1	0	9.8 %	24.9 %	72.2 %
AC	0.353553	1	0	9.8 %	24.9 %	72.2 %
BC	0.353553	1	0	9.8 %	24.9 %	72.2 %
A^2	0.26342	1.018265	0.017938	40.4 %	92.7 %	99.9 %
B^2	0.26342	1.018265	0.017938	40.4 %	92.7 %	99.9 %
C^2	0.26342	1.018265	0.017938	40.4 %	92.7 %	99.9 %
**Basis Std. Dev. = 1.0						

TABLE – 6. Measures derived

Measures Derived From the (X'X)^-1 Matrix			
S No	Std	Leverage	Point Type
1	1	0.669768	Fact
2	2	0.669768	Fact
3	3	0.669768	Fact
4	4	0.669768	Fact
5	5	0.669768	Fact
6	6	0.669768	Fact
7	7	0.669768	Fact
8	8	0.669768	Fact
9	9	0.607303	Axial
10	10	0.607303	Axial
11	11	0.607303	Axial
12	12	0.607303	Axial
13	13	0.607303	Axial
14	14	0.607303	Axial
15	15	0.16634	Center
16	16	0.16634	Center
17	17	0.16634	Center
18	18	0.16634	Center
19	19	0.16634	Center
20	20	0.16634	Center
	Average =	0.5	

The standard error of the design in represented in Fig. 3. Vickers micro hardness testing equipment was used for testing the interface micro-hardness of the joints. For one particular specification of the process parameters, three sets of values of micro-hardness were measured and the average of the three is taken.

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Fig. 3. Standard error of designs

TABLE – 7 ANNOVA response for surface quadratic model for Al micro hardness

Response	1	Al hardness				
	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	
Model	685.3442	9	76.14935	4.665848	0.0123	significant
A-R	3.970343	1	3.970343	0.243272	0.6325	
B-T	4.686292	1	4.686292	0.28714	0.6038	
C-D	18.00697	1	18.00697	1.103329	0.3183	
AB	0.5	1	0.5	0.030636	0.8645	
AC	0	1	0	0	1.0000	
BC	0	1	0	0	1.0000	
A^2	385.7628	1	385.7628	23.63659	0.0007	
B^2	243.8078	1	243.8078	14.93867	0.0031	
C^2	150.2814	1	150.2814	9.208088	0.0126	
Residual	163.2058	10	16.32058			
Lack of Fit	129.2058	5	25.84116	3.800171	0.0846	not significant
Pure Error	34	5	6.8			
Cor Total	848.55	19				

TABLE – 8 ANNOVA response for surface quadratic model for Cu micro hardness

Response	1	Cu hardness				
ANOVA for Response Surface Quadratic Model						
Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	
Model	696.8315	9	77.42572	2.976555	0.0522	not significant
A-R	4.320903	1	4.320903	0.166113	0.6922	
B-T	6.863741	1	6.863741	0.26387	0.6186	
C-D	18.00697	1	18.00697	0.69226	0.4248	
AB	0	1	0	0	1.0000	
AC	0.5	1	0.5	0.019222	0.8925	
BC	0	1	0	0	1.0000	
A^2	383.8563	1	383.8563	14.75698	0.0033	
B^2	242.2926	1	242.2926	9.314701	0.0122	
C^2	165.9309	1	165.9309	6.379051	0.0301	
Residual	260.1185	10	26.01185			
Lack of Fit	212.7852	5	42.55704	4.495462	0.0623	not significant
Pure Error	47.33333	5	9.466667			
Cor Total	956.95	19				

The "Deficit of Fit F-value" of 3.80 implies there is 8.46% chance that a "Deficit of Fit F-value" this large could occur due to noise.

III. RESULTS AND ANALYSIS

Analysis of variance (ANOVA) is an assemblage statistically built up models used to analyze the changes and the dissimilarities among the group means with their associated rules and regulations (such as "variation" among and between groups).

Using response surface methodology, ANOVA regression analysis is done and the results are tabulated. In Table 7, ANOVA response for surface quadratic model for Al micro hardness is given and in table 8, ANOVA response for surface quadratic model for Cu micro hardness is given.

In Al regression analysis, The Model F-value of 4.67 implies the model is significant. There is only a 1.23% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 is an absolute explanation that the terms in the models are significant. In this case A2, B2, C2 are significant model terms. Values greater than 0.1000 suggests that the model expressions are insignificant.

In Cu regression analysis, the Model F-value of 2.98 implies there is a 5.22% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 shows that model terms values are of significance.

In this case A^2, B^2, C^2 are significant model terms. Values more than 0.1000 shows that the model term values are not valid values. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of four and a half clearly determines that there is a 6.23 percent chance that a "Deficit of Fit F-value" this large could occur due to noise. Deficit (Lack) of fit is bad -- we want the model to fit.

In Fig. 4 and Fig. 5 normal and design plots for Cu micro hardness are given.

In Fig. 6 and Fig. 7 normal and design plots for Al micro hardness are given.

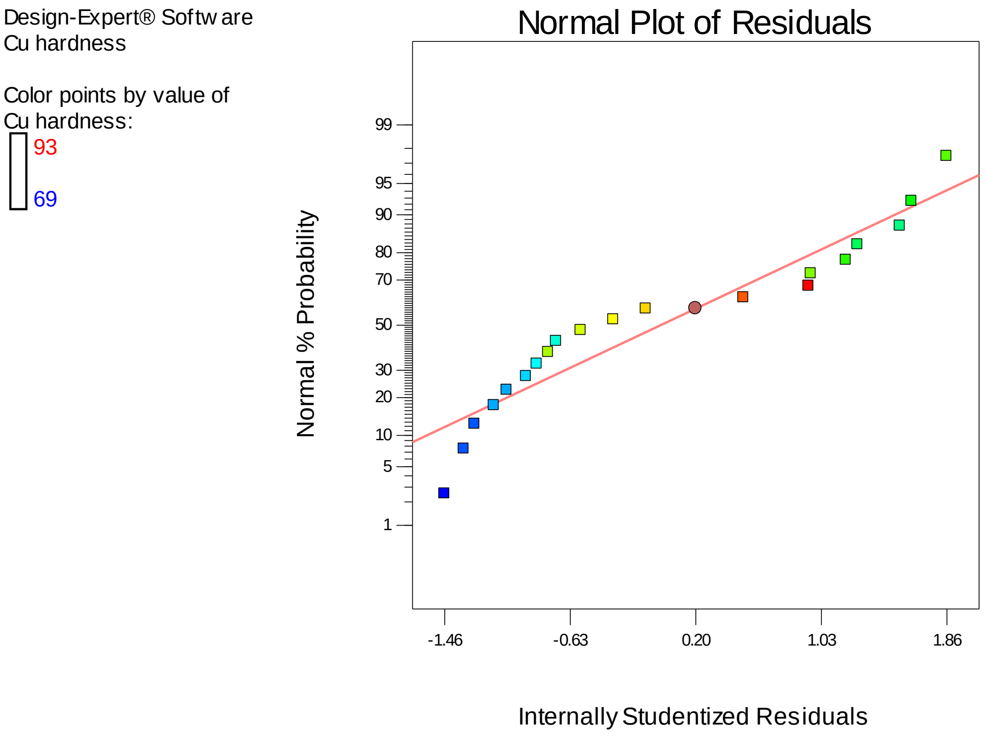


Fig. 4. Normal plots of residuals of Cu micro hardness

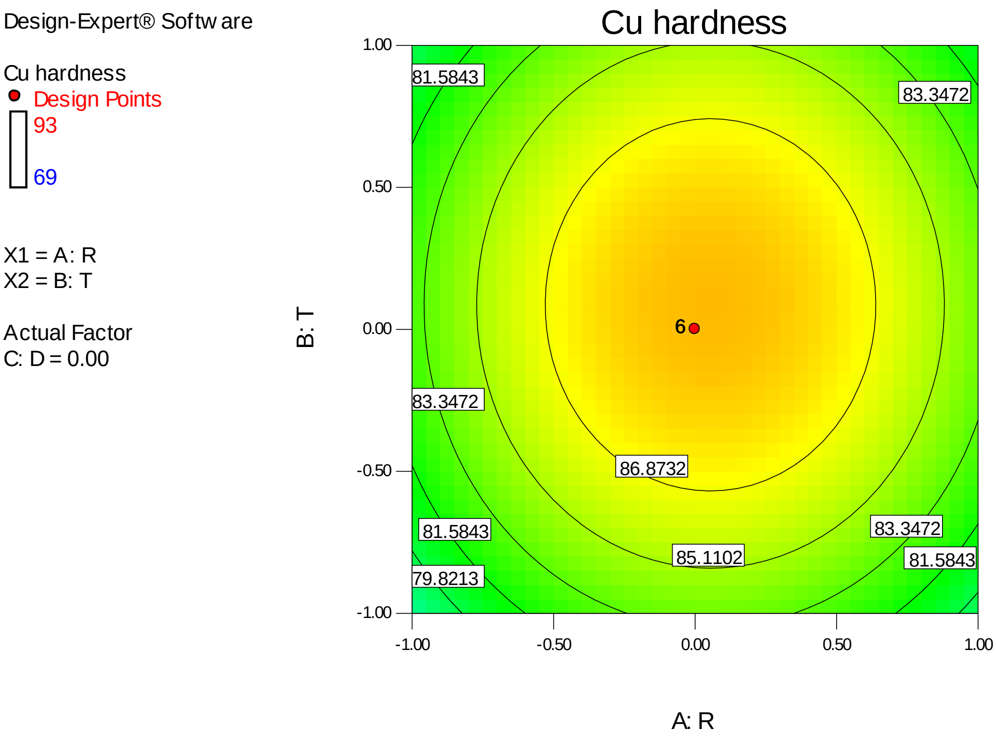


Fig. 5. Design plots of Cu micro hardness

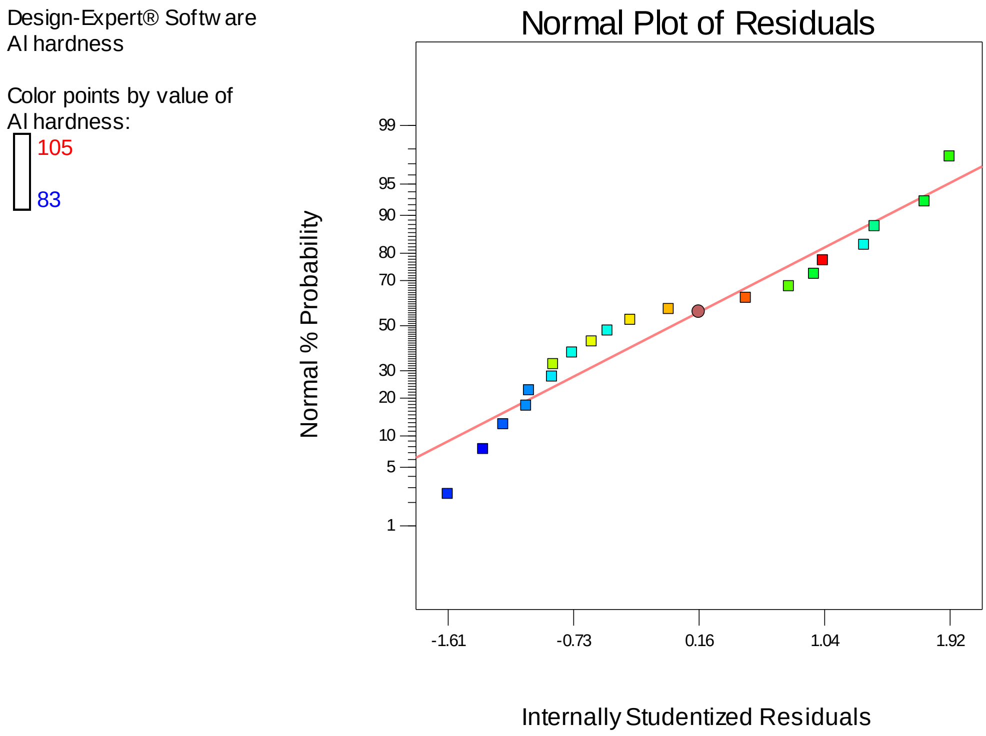
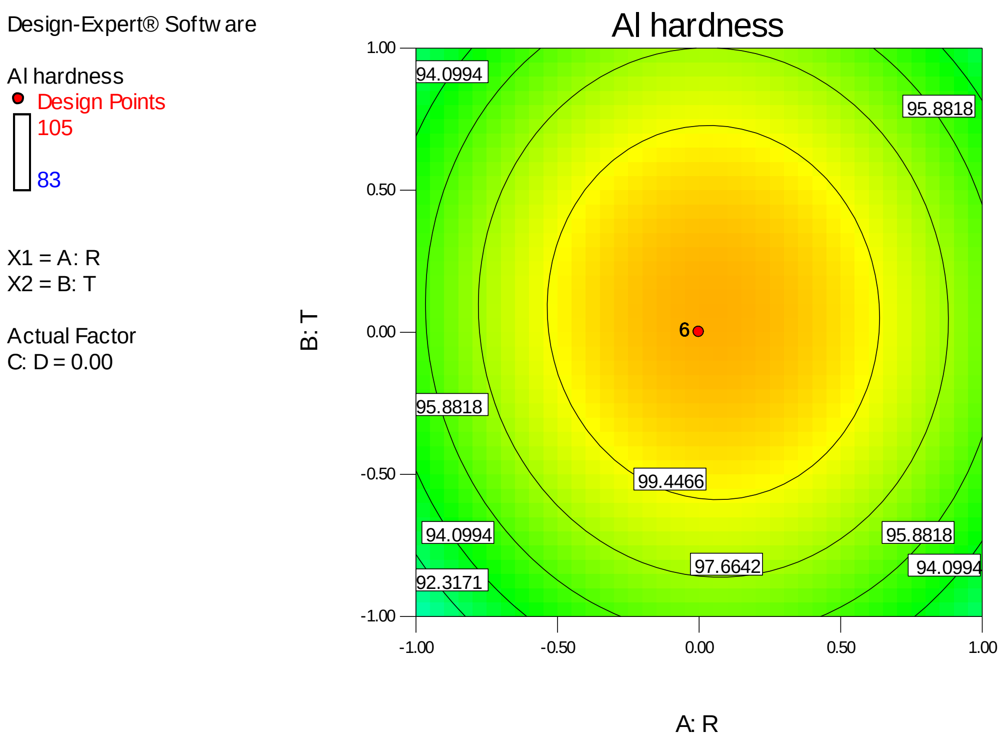


Fig. 6. Normal plots of residuals of Al micro hardness



IV. CONCLUSION

Fig. 7. Design plots of Al micro hardness

Thus using response surface methodology, optimization of friction stir spot welding process parameters of dissimilar joints of Al and Cu have been done.

Using three factor three level central composite design, the parameter values were taken for the experiments.

Using ANOVA analysis, the significance of the developed model were analyzed.

The design and normal plots generated gives the relationship between the material micro hardness with important process parameters such as dwell time, plunge depth and tool rotational speed.

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