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Fatigue Behavior of Dissimilar Metal Laser Spot Lap Weld Joints

Hrishikesh V. Ghule, Ashok P. Tadamalle
Department of Mechanical Engineering,
Sinhgad College of Engineering, Vadgaon, BK, Pune,
411041, Maharashtra, India

***Abstract*—The present work deals with the fatigue behavior of dissimilar metal 304 Stainless Steel and Galvanized Iron thin sheets of 0.8 mm thickness each, which were joined by laser spot welding method. Welding experiments were conducted as per design of experiment. The strength and nature of failure of weld specimen was investigated under tensile shear load. The optimal process parameters were identified to obtain maximum tensile shear strength using optimization tool of Design Expert. The experimental setup was developed for the fatigue life testing of laser spot weld specimens under different levels of constant amplitude tensile load cycles. To complement the experimental result the finite element static structural analysis was carried out by selecting hexahedral element. The S-N curve obtained through experimentation was compared with FEA. Optimization result suggested that the low level of laser power and welding time avoided for attaining better weld strength. The result reveals that the region around spot weld has the lowest fatigue life.**

Keywords—Tensile load cycles, dissimilar metal, optimization, laser spot weld, fatigue life

I. INTRODUCTION

Resistance spot welding is a popular welding method used for production of auto bodies in automobile industries. The increase in demand for better quality and strength of the weld joints having better weld appearance provokes the industry personnel to adopt laser welding instead of conventional welding methods. Laser welding has many advantages over traditional welding techniques such as low heat input, high processing speeds, capability of welding very thin sheets and huge potential for automation [1]. Laser welding is a highly complex process which generates significant amount of heat during welding resulting in increase in the hardness and weld strength. The multiple input process parameters have a great influence on the quality of the laser welded joints therefore, it is necessary to select the optimum input process parameters for the welding.

The welding process parameters were optimized using different optimization statistical tools such as Taguchi method, RSM, CCD, Box Behnken method [2-5]. The Nd:YAG laser welding of Ti6Al4V laser cladding process parameters were optimized using stastical technique and found that laser power, scanning speed and powder feed rate has influence on bead geometry [3]. Author [4] studied the influence of CO2 laser beam welding process parameters such as laser power, welding speed and focal distance on dissimilar metals of low carbon steel and austenitic stainless steel.

Also Also, welding causes some changes in the microstructure of the base metal near the weld zone. Microstructure of element has great influence on its mechanical properties, hence needed to be studied. Author [5] studied the characterization of dissimilar metal laser butt weld joints, made up of galvanized iron and 304L stainless steel sheets of 0.5 mm thickness. The authors studied the influence of Nd: YAG laser welding process parameters on 0.5 mm thick sheets to understand the overall behavioral characteristics of weld joint. The authors conducted the welding experiments as per Taguchi’s orthogonal array design matrix. Author examined these welding samples for the variation in the microstructure, chemical composition, weld defects, grain size, phase contents, microstrain and dislocation density across the weld joint. Authors [1,6-8] discussed the mechanical behavior which includes tensile properties, changes in microstructure, crack formation and its propagation in welded joints, which are of either similar or dissimilar metals under monotonic tension, or shear or fatigue loading. There are several variants of the structural stress or strain concepts, of the notch stress or strain and of the fracture mechanics concepts of fatigue assessment of welded joints discussed by D. Radaj et al. In recent developments of fatigue assessment of welded joints localized stress approach or Hot spot technique, conventional and modified structural stress concept, finite element approach are used to find the solution [9].

In this study the diode laser is used to join the overlapped dissimilar metal sheets using spot welding. The most significant welding process parameters and their range were selected and subsequently the welding experiment was carried out. For fatigue testing welding experiment was carried out at optimum values of welding process parameters and specimens were prepared as per AWS standards. The fatigue test of the welded specimens were simulated and presented in this paper using finite element software package of ANSYS workbench and validated with the experimental results.

II. EXPERIMENTAL ANALYSIS

A) Design of Experiment

The welding experiments were conducted to predict the fatigue life of laser weld joints. The significantly affecting input process parameters on response parameters of weld joints were identified from literature review. Among these parameters some can be controlled while others can’t. It is necessary to identify most significantly affecting parameters for conducting experiments as per design of experiment. A Laser Power, Welding Time and Focal Position were selected as significantly affecting welding process parameters based on literature review [1-4] and advice from the experts. The experiments were conducted as per Box-Behnken method to estimate optimal responses using Design Expert tool. TABLE I depicts the welding process parameters and their levels.

In current study the response variable is the tensile shear strength of the weld. These welding experiments were designed by Box-Behnken method using Design Expert software. This method gave DOE matrix of three columns and 15 rows. For this study three welding process parameters with three levels each were chosen. The respective welding process parameters and their levels are listed in TABLE I.

TABLE I: Laser welding process parameters and their levels

No.	Process parameters	Units	Levels	
			-1	+1
1	Laser Power	W	1000	3500
2	Welding Time	s	0.5	1.2
3	Focal Position	mm	-0.4	0.4

B) *Material Selection and Welding Process*

The weld samples of 120 mm × 25 mm were cut from 0.8 mm thick sheets of Galvanized Iron and 304 Stainless Steel metal sheets. The reason for selection of dissimilar metal material for the study is based on availability, weldability, mechanical properties and cost. The edges of the specimens to be welded were fine finished to match the weld specimens perfectly during welding. The welding experiments were performed on KUKKA make "diode laser machine" having maximum power capacity of 4 kW equipped with ABB robot is as shown in Fig. 1.

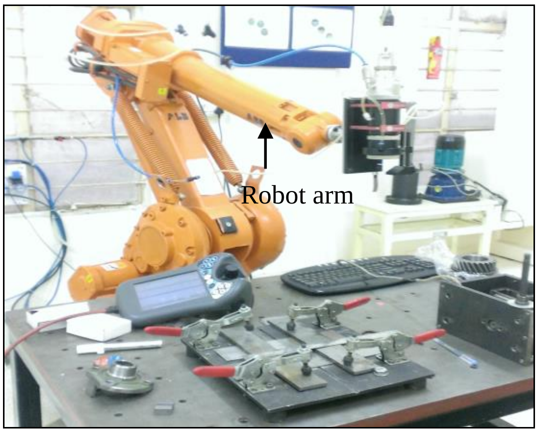

Fig. 1 Laser welding experimental setup

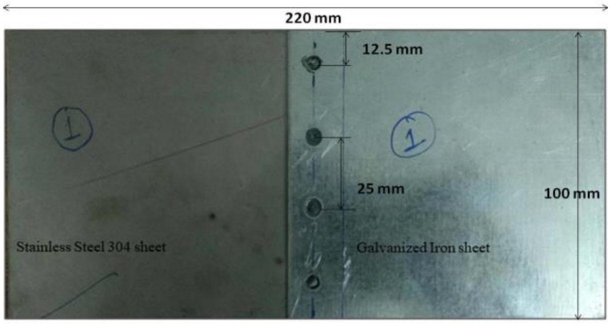

Fig. 2 laser spot weld specimens

The laser spot weld specimen dimensions and the overlapping length is shown in Fig. 2. The centre distance between two consecutive spot was kept as 25 mm. From top and bottom side of sheet to the centre of spot, 12.5 mm distance was kept.

C) *Tensile Test*

Under uniaxial tensile load, lap weld joints fail mainly due to shear, therefore tensile shear strength experiments were conducted to find the tensile property. The Fig. 3 shows the dimensions (in mm) of the welded specimen to be cut as per AWS standards [1, 10].

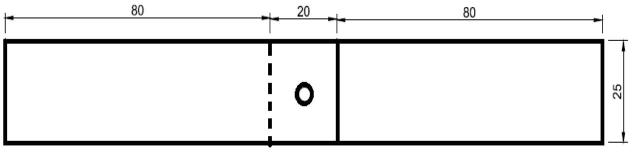

Fig. 3 Geometry of tensile shear test specimen

1) *Tensile Test Setup*

The uniaxial tensile load was applied on the welded specimens with the help of universal testing machine, as shown in Fig. 4. Force displacement graph of all the 15 specimens were recorded using computer.

Fig. 4 Universal testing machine setup

The load versus displacement graph of sample number 13 is shown in Fig. 5. It shows a peak load of 3.06 kN and corresponding elongation as 3.43 mm. Similarly, load versus elongation graph of all the 15 samples were obtained to find out the peak load and the tensile shear strength of all the samples were calculated using equation (1),

$$Fp = \sigma_{TS} \times \frac{\pi}{4} \times d \times d \qquad (1)$$

where 'Fp' is peak load, 'σ_{TS}' is the tensile shear strength and 'd' is the spot diameter. TABLE II shows the tensile shear strength values obtained from experimentations and are presented in design of experiment matrix.

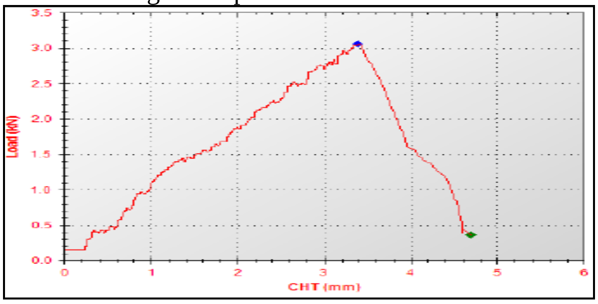

Fig. 5 Load vs displacement plot of sample 13

TABLE II: Experimental results of tensile shear specimen

Std. Order	LP (W)	WT (sec)	FP (mm)	TSS (MPa)
1	3500	0.5	0	159.72
2	1000	0.85	-0.4	144.68
3	1000	0.85	0.4	145.71
4	2250	0.85	-0.4	165.53
5	3500	1.2	0	272.32
6	2250	0.5	-0.4	177
7	2250	0.85	0.4	221.137
8	2250	0.85	0	147.978
9	1000	1.2	0	148.556
10	3500	0.85	0.4	231.01
11	2250	0.5	0.4	169.42
12	3500	0.85	-0.4	181
13	2250	1.2	0.4	318.05
14	1000	0.5	0	110.62
15	2250	1.2	-0.4	155.348

D) Response Surface Methodology

Response surface methodology (RSM) is used to predict the relationship between welding process parameters and the response. The RSM is worth to describe the process and to maximize the response value [4]. A quadratic response surface model was selected to evaluate the effects of laser welding process parameters on the tensile shear strength.

1) ANOVA Test

ANOVA is applied to judge how adequate is the mathematically fitted model based upon test of significance of the fitted models, F-test, and the Lack-of-Fit test. The result of the ANOVA test along with significant model terms and R^2 values are shown in the TABLE III. The p-value of model is less than 0.05, indicates that the model was significant. There is only a 0.83 % chance that this large F-value (11.05) of the model could occur due to noise. In ANOVA table, values of Probability > F or p-value less than 0.05 indicates that the model terms are significant. Therefore interaction between model terms A, B, C, AC, and BC considered as significant. The p-value of Lack of Fit is 0.4032 and implies that the Lack of Fit is not significant. This p-value suggests that there is a 40.32 % chance of having this much large value, which could occur due to noise. Not-significant Lack of Fit value and R-Squared value as 95.24 % are good because it suggests that the defect in this model is not too significant, hence this model can be used for the design space.

TABLE III: ANOVA for response surface quadratic model

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob > F
Model	40296.86	9	4477.43	11.05	0.0083 significant
A-Laser power	10840.10	1	10840.10	26.76	0.0035
B-welding time	9626.75	1	9626.75	23.76	0.0046
C-Focal position	6852.30	1	6852.30	17.01	0.0091
AB	1393.68	1	1393.68	3.46	0.1219
AC	599.76	1	599.76	1.49	0.2767
BC	7248.99	1	7248.99	18.00	0.0081
A^2	165.20	1	165.20	0.41	0.5501
B^2	1443.28	1	1443.28	3.58	0.1169
C^2	1921.41	1	1921.41	4.77	0.0807
Residual	2013.61	5	402.72		
Lack of Fit	1871.39	4	467.85	3.04	0.4032 not significant
Pure Error	154.04	1	154.04		
Cor Total	42322.29	14			
R-Squared					0.9524
Adj R-Squared					0.8668
Adeq Precision					11.751

Fig. 6 shows the relationship between the predicted and the actual values of tensile shear strength of laser spot weld specimens. It reveals that the developed models are adequate since the predicted results are in good agreement with the actual measured values. The predicted values are close to actual values and scattered around the straight line.

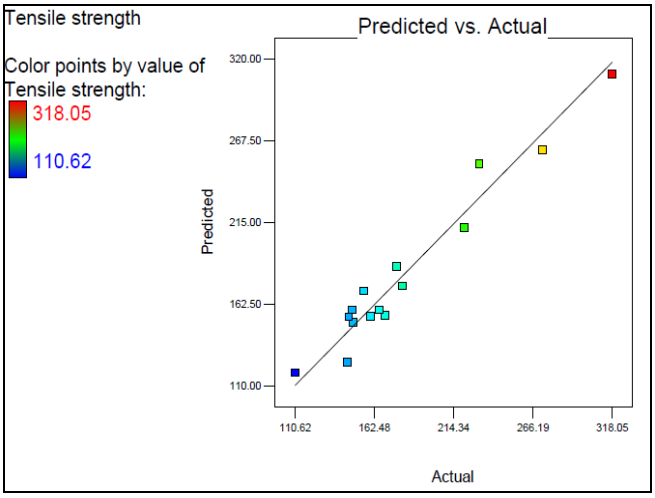

Fig. 6 Plot for predicted vs. actual response

2) Response Surface Graph

Response surface graphs are used to find the optimal response point for the respective values of significantly affecting process parameters. Fig. 7 shows the influence of welding time and laser power on the tensile strength and it is observed that the tensile strength improves with increase in the welding time and the laser power. This happen may be due to formation of bigger nugget diameter in the laser spot welded specimens which were undergoing higher levels of laser power and welding time.

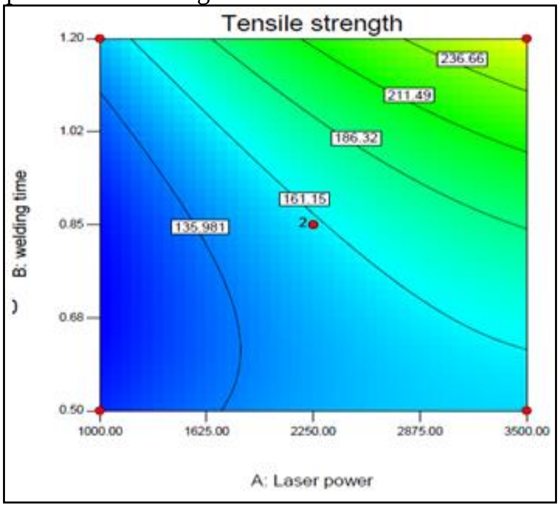

Fig. 7 Influence of Laser Power and Welding Time on the tensile strength

3) *Optimization*

The Design Expert optimization tool was used to optimize the tensile shear strength of the spot weldment for the given range of process parameters. The optimal result is shown in the Fig. 8. It is observed that, the Laser Power of 2667.29 W, Welding Time of 1.18 seconds and Focal Position of 0.39 mm are the optimum values of process parameters which provides the tensile strength of 321.739 MPa.

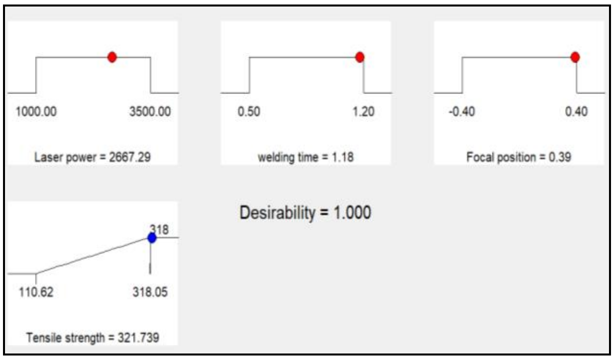

Fig. 8 Optimal solution for tensile shear strength

E) Fatigue Test

The customized fatigue test setup was designed and developed to test the specimens under cyclic loading. The details of each component of fatigue test setup are shown in Fig. 9.

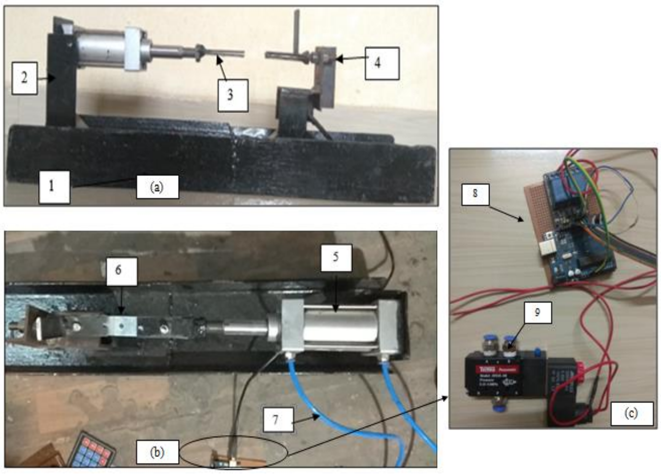

Fig. 9 Fatigue test setup (a) Front view, (b) Top view and (c) enlarged view. 1- I-channel, 2- L-channel, 3- gripping plates, 4- nut-bolt assembly, 5- pneumatic cylinder, 6- tensile shear fatigue specimen, 7- air carrying pipe, 8- electronic circuit and 9- direction control valve

For generating the reciprocating motion and load application, the double acting pneumatic cylinder of bore diameter was fixed on the L-channel. For the transmission of the applied load to the laser spot welded specimen gripping fixture was made. The electronic circuit and direction control valve are used for maintaining the desired load and frequency throughout the test.

The experiments for fatigue test were conducted on the specimens, welded at optimal values of process parameters. The five specimens were welded at same values of process parameters and cut according to the AWS standard and were tested under the load of 10 %, 20 %, 40 %, 45 %, and 52.35 % of the maximum load of 3 kN. This value of maximum load is because of the fact that the maximum load sustained by the specimen was approximately equal to 3 kN under tensile test. Authors [1, 6-10] conducted the fatigue tests at certain percentage of the peak load which was obtained from tensile test. The TABLE IV shows the experimental results of Alternating stresses obtained at applied loads. The stress ratio R = 0 at different load levels and a pneumatic cylinder under load control at a frequency of 50 Hz was used while conducting the fatigue experiments.

TABLE IV: Alternating stresses at applied loads

No	Applied Load in N	Alternating Stress in MPa
1	308.07	15.59
2	616.14	31.1813
3	1193.8	62.3635
4	1350	70.15
5	1540.40	80.05

The maximum stress acting on the specimen, while conducting the fatigue test under different load was calculated using Equation (2).

$$\sigma_{max} = \frac{F}{\frac{\pi}{4} \times d \times d} \qquad (2)$$

The alternating stress can be expressed by Equation (3),

$$\sigma_{Alt} = \frac{(\sigma_{max} - \sigma_{min})}{2} \qquad (3)$$

where ‘*F*’ is the load, ‘*d*’ is the spot diameter, ‘σ_{Alt}’ is the alternating is stress, ‘σ_{max}’ is the maximum stress and ‘σ_{min}’ is the minimum stress which is zero.

F) Finite Element Analysis

The purpose of the finite element analysis was to validate the experimentally calculated fatigue life results. Three dimensional finite element analyses of laser spot welded specimens were conducted to find out the fatigue life of the specimens under the different loading conditions. The loading conditions which were used in actual experimental work were replicated directly for finite element analysis. The finite element mesh model of the laser spot weld with Hex dominated Fine and On Curvature type mesh is shown in Fig. 10. The material properties like Young’s modulus of stainless steel 304 and galvanized iron were taken from manufacturer catalogue.

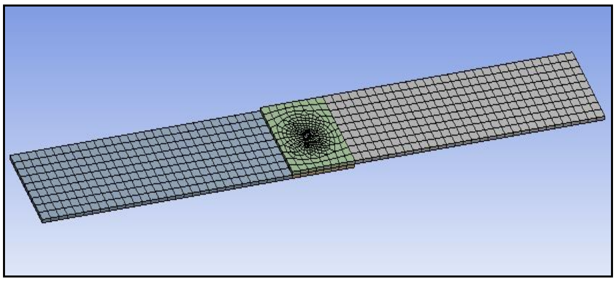

Fig. 10 Mesh model of the laser spot weld specimen

1) Boundary Conditions

In Fig. 11, a uniaxial force of 1350 N was applied on each sheet but in opposite direction [11]. The analysis was completed in static structural module of the Ansys workbech.

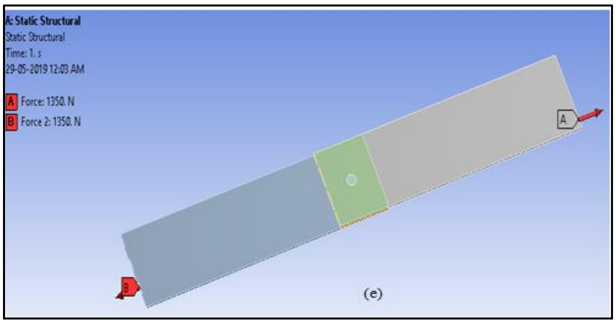

Fig. 11 Loading Boundary condition for fatigue

III. RESULT AND DISCUSSIONS

The fatigue strength and service life of the laser spot lap joints is affected by parameters like geometry, type of loading, materials, and changes in microstructure. The fatigue behavior of the dissimilar metal laser spot weld joints was studied under constant amplitude tensile loads. The results obtained from experimental and numerical methods have been discussed below.

The laser spot welded specimens obtained after failure under tensile shear loading are shown in Fig. 12. Fig.12 (a) shows the mode of failure in specimen number 13; initially it was partially pulled out and then the Galvanized Iron sheet of the weld spot subjected to tearing. Fig. 12 (b) shows a pullout failure mode, where weld nugget of specimen 11, is completely pulled out from the Galvanized Iron metal sheet by creating a hole. Interface failure was observed in the specimen 10 and is shown in Fig. 12 (c). Fig. 12 shows the load carrying capacity of specimens failed under interfacial mode, is less than that of specimens failed under pullout mode.

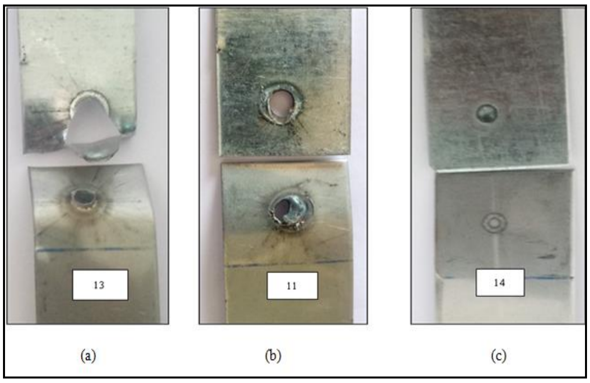

Fig. 12 Modes of failure (a) pullout succeeded by sheet tearing; (b) pullout; (c) interfacial

The fatigue behavior of laser spot welded specimens under the constant amplitude loading conditions (stress ratio R = 0) were studied by carrying out experimental work with the help of fatigue test setup. The run-out limit for the laser spot welded fatigue specimens was decided to keep as one million cycles. This means that the fatigue specimens which are reaching one million cycles without forming crack on its surface were considered as run-outs. The fatigue specimens 1 and 2 were tested under constant amplitude axial load of 308.07 N and 616.14 N respectively. Specimens 1 and 2 didn't show any sign of crack on their surface and had successfully sustained the load for one million cycles hence considered as run-out.

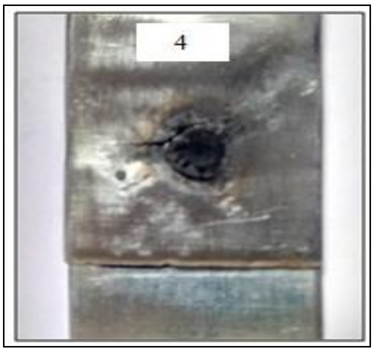

Fig. 13 Fatigue crack formation in the laser spot welded fatigue specimen

The specimens 3, 4 and 5 were tested at the constant amplitude axial load of 1193.8 N, 1350 N and 1540.36 N respectively. Since these specimens were tested under higher levels of tensile loading cycles compared to specimens 1 and 2, showed crack on their surfaces. Fig. 13 shows the crack developed on the surface of the specimen 4 at the region around the spot. The fatigue failure shown by specimens 3, 4 and 5 is in transverse direction. Authors [1, 7] have also found similar kind of failure pattern under axial fatigue load.

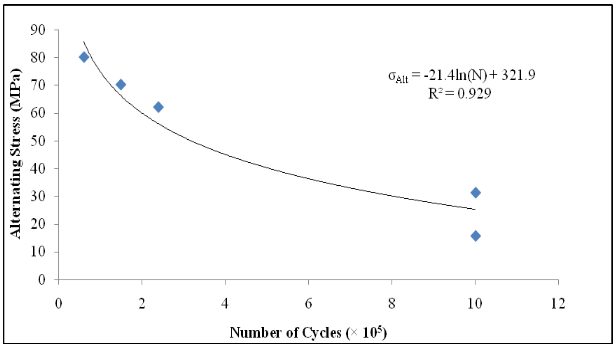

Fig. 14 Experimentally obtained S-N curve for laser spot welded fatigue specimens

The experimentally obtained alternating stress (S) versus number of cycles (N) graph for all the five specimens were plotted and shown in Fig. 14. The specimens were tested at alternating stress values taken from the TABLE IV and the corresponding fatigue lives of the specimens were measured. The regression coefficient of experimentally obtained S-N curve is $R^2 = 0.929$.

The numerical simulation was carried out using finite element software Ansys Workbench 16. The fatigue life result of the specimen 4 for the 1350 N load was obtained using the software and shown in the Fig. 15. Similarly for different load levels, fatigue life of all the five specimens were calculated and S-N curve is plotted for the obtained results.

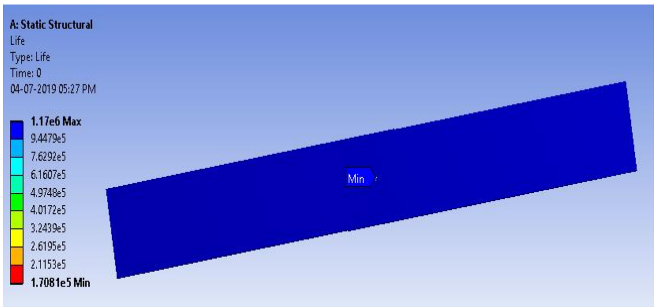

Fig. 15 Fatigue life obtained under 1350 N load using FEA

Fig. 16 shows the S-N curve obtained for laser spot welded specimens using numerical method. The R^2 value of the plot shows that the 95.5 % of the values fit the model. This R^2 value of the curve fitting for the numerical method is higher than that of the experimentally obtained S-N curve.

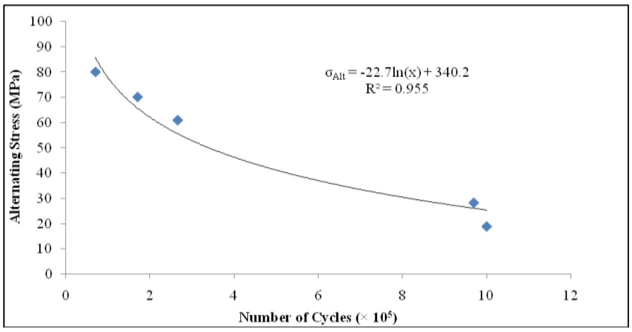

Fig. 16 S-N curve for welded specimens using FEA

Fig. 17 shows the fatigue life results of specimens 1 to 5, the result depicts that there is negligible difference in results obtained from experimental and numerical method, because these samples are tested under lower value of fatigue loads; whereas sample numbers 3, 4 and 5 reveals higher fatigue life than experimental.

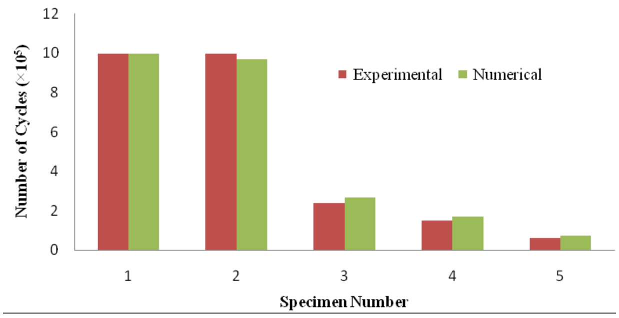

Fig. 17 Comparison of fatigue life

CONCLUSION

The study of fatigue behavior of overlapped dissimilar metal laser spot welds of Galvanized Iron and 304 Stainless Steel sheets reveals the following conclusions:

- Laser Power, Welding Time and Focal Position were identified as significantly affecting process parameters.
- The Laser Power and Welding Time contribute to the strength of the weld joint.
- There are prominently two modes of failure observed in tensile testing namely, pullout and interfacial. In pullout type failure mode, elongation of galvanized iron sheet occurs and ends with tearing of sheet.
- The region around the spot has the lowest fatigue life.
- The fatigue life results obtained from experimental and FEA at lower level cyclic loads have better agreement as compared to the higher loads.

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