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Optimal Process Parameters to Achieve Maximum Tensile Load Bearing Capacity of Laser Weld Thin Galvanized Steel Sheets

Mooli Harish, V Shanmukha Prasad, M.B.S Sreekara Reddy, Koora Rajanikanth, B Nageswara Rao

Abstract*:** *Steels are protected against corrosion through hot-dip galvanization in which material surfaces are coated with molten zinc. Galvanized steel products are reliable in coating life and performance with lower maintenance and repair cost.* ***Welding of such zinc coated steel sheets is of great economic importance in the automotive industries. Many researchers have utilized the S/N ratio transformation while obtaining the optimal solution of several manufacturing processes. However, the additive law in Taguchi technique estimates the deterministic output response from the mean values of the ANOVA table and unable to provide the expected range of the output response. This paper deals with optimal process parameters for achieving maximum tensile load bearing capacity of laser weld thin galvanized steel sheets utilizing the concepts of a modified Taguchi design of experiments. Excepted range of the tensile load bearing capacity is provided for the specified laser process parameters. Empirical relation is developed and validated for the tensile load bearing capacity in terms of the laser process parameters viz., laser power, welding speed and focal point position.

Keywords* : *Focal point position; Galvanized steel; Laser overlap welding; Laser power; Modified Taguchi approach; Welding speed; Tensile load.

I. INTRODUCTION

The automotive industries are currently focussing on the low cost, lightweight, crashworthy and durable galvanized steel materials. Welding of such zinc coated steel sheets is of great economic importance. The conventionally resistance spot welding process of thin sheets require two side access and have excessively short electrode life [1]. Laser welding is the best choice for such materials [2]. To improve weld quality of galvanized steel sheets in zero gap lap joint formation, the zinc coatings at the faying surface are vaporized [3]. Yang et al. [4] have indicated the possibility of achieving full penetration sound welds at low welding speed. Chen et al. [5] have utilized vent holes for strong weld formation through riveting mechanism. Benyounis and Olabi [6] have made a review on several optimal welding processes. Zhao et al. [1] have utilized the response surface method (RSM) to study the effects of laser welding process parameters on weld bead profiles, and stated the necessity of a prescribed gap to vent the pressurized zinc vapor for durable joints. Anawa and Olabi [7] have adopted Taguchi technique to enhance the productivity of laser welding steel sheets with minimum operation cost. Sathiya et al. [8] have adopted Taguchi approach and performed desirability analysis relating the laser process parameters to the weld bead profiles and joint strength. Yuce et al. [9] have made an interesting experimental study to optimize the laser welding process for achieving maximum tensile load bearing capacity of thin galvanized steel sheets adopting the Taguchi's L_9 orthogonal array and using the signal-to-noise (S/N) ratio transformation. In fact, Taguchi has introduced the concept of S/N ratio transformation to account the scatter in the output response from repeated tests and to provide a single value for performing analysis of variance (ANOVA) to understand the significance of process parameters. Design and manufacturing group of authors contributed a lot relevant to the development of materials [10–17], fabrication aspects [18–20], and industrial/engineering optimization problems [21–23] for the benefit of the readers of the journal.

Taguchi method is a simple and systematic statistical approach. It is being utilized for solving industrial/engineering optimization problems (such as controlling of drilling induced damages in composites, significance of parameters in the stage and satellite separation processes, as well as on the performance of chevron type plate heat exchangers and other manufacturing processes) [24–31].

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***** Correspondence Author

Mooli Harish*, Assistant Professor, Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Deemed to be University, Green Fields, Vaddeswaram, Guntur-522 502, India.

V Shnmukha Prasad*, Assistant Professor, Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Deemed to be University, Green Fields, Vaddeswaram, Guntur-522 502, India.

M B S Sreekara Reddy, Assistant Professor, Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Deemed to be University, Green Fieleds, Vaddeswaram, Guntur-522 502, India. **Koora Rajanikanth**, Assistant Professor, Department of Mechanical Engineering, CMR Technical Campus, Kandlykoya, Medchal, Hyderabad-501 401, India.

B Nageswara Rao, Professor, Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Deemed to be University, Green Fields, Vaddeswaram, Guntur-522 502, India.

This paper examines the simplicity and the adequacy of Taguchi approach to trace optimal process parameters for achieving the maximum tensile load bearing capacity of the laser weld thin galvanized steel sheets. It follows the modified Taguchi method [32–35] in finding the expected range of the output responses and Taguchi's simple single-objective optimization technique. Empirical relation for the maximum tensile load bearing capacity of laser weld thin galvanized steel sheet is developed in terms of process parameters and validated with test results. The test results are found to be within the expected range.

II. TEST DATA ACQUISITION

Yuce et al. [9] have performed experiments on thin galvanized steel sheets to trace optimal laser welding process parameters for maximum tensile load bearing capacity by adopting the Taguchi's L_9 orthogonal array and using the signal-to-noise (S/N) ratio transformation. The steel sheets have rectangular geometric shape and the dimensions are 185mm of length, 80mm of width and 0.75mm of thickness. They have used IPG ytterbium fiber laser and 10 l/min Ar shielding gas in welding experiments. They have assigned three levels for three laser welding process parameters, viz., laser power, welding speed and focal point position. For the metallographic examination, the samples are cut from the weld cross-section and mounted in Bakelite for grounding and polishing. 3% Nital solution is applied to study the grain boundaries and weld zone microstructures. Tensile samples as per ASTM E8 standards are machined normal to the welding direction and tested for recording the tensile load bearing capacity of laser welded thin galvanized steel sheets. They have presented the average tensile bearing load of three tests.

III. DEVELOPMENT OF EMPIRICAL RELATION BASED ON THE TAGUCHI'S DESIGN OF EXPERIMENTS

In a systematic statistical Taguchi approach, the data of full factorial design of experiments can be generated from few experiments. If n_p is the number of process parameters and n_l is the number of levels assigned for each process parameter, then $n_i^{n_p}$ tests are to be performed for full factorial design of experiments. As per the Taguchi design of experiments, the number of experiments ($N_{Taguchi}$) required is [37].

$N_{Taguchi}$ = 1 + (Number of process parameters) × (Number of assigned Levels-1)

$$= 1 + n_p \times (n_l - 1) \quad (1)$$

For Taguchi's L_9 orthogonal array, number of test runs, $N_{Taguchi}$ = 9, which can accommodate the number of process parameters, $n_p = 4$ for the number of assigned levels, $n_l = 3$, whereas in case of full factorial design of experiments, one has to conduct $n_l^{n_p} = 3^4 = 81$ tests.

A. *Analysis of Variance (ANOVA)*

The design of experiments in [9] involves three process parameters (such as laser power, welding speed and focal point position, which are designated by A, B and C for easy of reference) with three levels in the selected L_9 orthogonal array. Levels of laser welding process parameters and the tensile load (T_L) bearing capacity of laser weld thin galvanized steel sheets as per L_9 orthogonal array are presented in Table-I.

When $N_{Taguchi}$=9 and number of levels $n_l = 3$, equation (1) gives four number of factors that can be accommodated. As in [36], a fictitious factor (fourth factor) D is also introduced in Table-I. The sensitiveness of the change in the level setting is worked out by evaluating the sum of the squares (SOS) of deviation of each of the mean value from the overall mean. %Contribution is obtained by dividing the sum of the squares of each process parameter with the total sum of the squares. Analysis of variance (ANOVA) is thus performed to trace the optimal process parameters for achieving maximum tensile load (T_L) bearing capacity of the laser weld thin galvanized steel sheets. Regarding the individual contribution of process parameters on the output response (T_L), it is noted from the ANOVA results of Table-II that focal point position (C) has maximum effect on the tensile load (T_L) with 38.2% contribution and other parameters like laser power (A) and welding speed (B) on the tensile load (T_L) are 23.9% and 4.4% respectively. Sum of the % Contributions including the fictitious parameter (D) in the ANOVA results of Table-II for the output response is 100. Hence, Error (%) with inclusion of the fictitious parameter (D) is zero, whereas with exclusion of D, the Error (%) is equal to that of the %Contribution of D.

This is the reason why the additive law (2) predicts the output responses close to the test results with inclusion of the fictitious parameter (D) with no additional experimentation by adding additional column in the Taguchi's L_9 orthogonal array.

B. *Expected range of the output response*

The expected range of the output response is required for accounting the scatter in repeated experiments. It is possible to establish empirical relations for the output responses in terms of input variables. From the ANOVA results of Table-II, the estimates of tensile load (T_L) for the assigned levels of process parameters in Table-2 are presented in Table-III. The additive law [28] for estimating the tensile load (TL) for each test run is

$$\hat{T}_L = (T_L)_{mean} + \sum_{i=1}^{n_p} \left\{ (T_L)_i - (T_L)_{mean} \right\} \quad (2)$$

Here $\hat{T}_L$ is the estimated tensile load; $(T_L)_{mean}$ is the overall mean of T_L; $(T_L)_i$ is the mean value of T_L for the specified level of the process parameter (i); and n_p is the number of process parameters. The estimated tensile load in Table-4 for the 9 test runs are found to be reasonably in good agreement with test results. It should be noted that $n_p = 3$ in equation (2) corresponds to the estimates of T_L with exclusion of fictitious parameter (D), whereas $n_p = 4$ corresponds to the estimates of T_L with inclusion of fictitious parameter (D). With inclusion of fictitious parameter (D), the estimates of T_L in Table-III are very close to the test results. Considering the levels of lowest and highest mean values of T_L for the fictitious parameter (D) the expected range of T_L is arrived. The test results in Table-III are found to be within the expected range. In the present case study, nine tests are required as per the Taguchi design of experiments for three process parameters with three levels. The additive law [37] in Equation (2) provides the estimates of T_L in Table-IV for all possible 27 combinations of process parameters.

Empirical relation developed from the mean values of T_L in terms of the process parameters viz., laser power (A), welding power (B) and focal point position (C) is

$$T_L = 0.9361 + 0.03133\xi_1 + 0.04367\xi_1^2 - 0.012\xi_2 - 0.02133\xi_2^2 - 0.046\xi_3 + 0.03767\xi_3^2 \quad (3)$$

Here, $\xi_1 = 2\times10^{-3}A - 5$; $\xi_2 = 0.1B - 10$; and $\xi_3 = -1 - C$.

Applying the corrections -0.0534 and +0.0382 to the results of equation (3), one can find the lower and upper bounds of T_L. The test results in Table-V are within the expected range using the developed empirical relation (3). In the response surface methodology (RSM), a truly quadratic model for the tensile load bearing capacity (T_L) involving cross-terms of the process parameters.

Empirical relation (3) is developed from the three mean values of T_L and the corresponding level values of each process parameter. Equations (2) and (3) provide the same results.

For the maximum value of T_L, the optimal process parameters from the ANOVA table are $A_3B_2C_1$.Subscript denotes the level of the process parameter. The set of optimal process parameters are: laser power, *A*=3000 W; welding speed, *B*=100 mm/sec; and pocal point position, *C*=0 mm. For these process parameters, the expected range of T_L is from 1.0413 to 1.1331 kN, which confirms the test results of the test run-8 in Table-I.

The microstructural examination reveals fusion zone (FZ), heat affected zone (HAZ) and base metal (BM). The BM region shows a ferritic microstructure with relative homogeneous grain size. The narrow HAZ consists of mainly coarse ferrite. The FZ contained a large amount of acicular ferrite and small areas of bainite. The microhardness values of the FZ, HAZ and BM are 173.7, 109.8 and 92.2 (HV0.1) respectively.

Table-I: Tensile load bearing capacity, T_L (kN) of laser weld thin galvanized steel sheets

Levels of laser weld process parameters

Process parameters	**Designation**	**Level-1**	**Level-2**	**Level-3**
Power (W)	A	2000	2500	3000
Speed (mm/sec)	B	90	100	110
Focal point position (mm)	C	0	-1	-2
Fictitious	D	d_1	d_2	d_3

L_9 orthogonal array

Test Run	**Levels of process parameters**				**Tensile load bearing capacity, T_L (kN) [11]**
	A	**B**	**C**	**D**	
1	1	1	1	1	1.038
2	1	2	2	2	0.895
3	1	3	3	3	0.945
4	2	1	2	3	0.965
5	2	2	3	1	0.943
6	2	3	1	2	0.933
7	3	1	3	2	0.940
8	3	2	1	3	1.133
9	3	3	2	1	0.993
Overall Mean					**0.9761**

Table-II: Analysis of variance (ANOVA) on tensile load bearing capacity, T_L (kN)

Parameters	1-Mean	2-Mean	3-Mean	Sum of squares	% Contribution
A	0.9593	0.9470	1.0220	0.009704	23.9
B	0.9810	0.9903	0.9570	0.001774	4.4
C	1.0347	0.9510	0.9427	0.015534	38.2
D	0.9913	0.9227	1.0143	0.013647	33.6

Table-III: Estimates of the tensile load bearing capacity, T_L (kN) and comparison with test data

Test Run	Levels of process parameters				Test [11]	Estimate Eq. (2)			Expected range	
	A	B	C	D		$n_p = 3$	R.E. (%)	$n_p = 4$	Lower bound	Upper bound
1	1	1	1	1	1.038	1.0228	1.5	1.038	0.9693	1.0611
2	1	2	2	2	0.895	0.9484	-6.0	0.895	0.8950	0.9868
3	1	3	3	3	0.945	0.9068	4.0	0.945	0.8533	0.9451
4	2	1	2	3	0.965	0.9268	4.0	0.965	0.8733	0.9651
5	2	2	3	1	0.943	0.9278	1.6	0.943	0.8743	0.9661
6	2	3	1	2	0.933	0.9864	-5.7	0.933	0.9330	1.0248
7	3	1	3	2	0.940	0.9934	-5.7	0.940	0.9400	1.0318
8	3	2	1	3	1.133	1.0948	3.4	1.133	1.0413	1.1331
9	3	3	2	1	0.993	0.9778	1.5	0.993	0.9243	1.0161

Table-IV: Estimates of tensile load bearing capacity, T_L (kN) for the full factorial design of experiments

S. No.	Levels of process parameters			Tensile load bearing capacity, T_L (kN)			
	A	B	C	Eq. (2)	Lower Bound	Upper Bound	Test [11]
1	1	1	1	1.0228	0.9693	1.0611	1.038
2	1	1	2	0.9391	0.8857	0.9774	
3	1	1	3	0.9308	0.8773	0.9691	
4	1	2	1	1.0321	0.9787	1.0704	
5	1	2	2	0.9484	0.8950	0.9868	0.895
6	1	2	3	0.9401	0.8867	0.9784	
7	1	3	1	0.9988	0.9453	1.0371	
8	1	3	2	0.9151	0.8617	0.9534	
9	1	3	3	0.9068	0.8533	0.9451	0.945
10	2	1	1	1.0104	0.9570	1.0488	
11	2	1	2	0.9268	0.8733	0.9651	0.965
12	2	1	3	0.9184	0.8650	0.9568	
13	2	2	1	1.0198	0.9663	1.0581	
14	2	2	2	0.9361	0.8827	0.9744	
15	2	2	3	0.9278	0.8743	0.9661	0.943
16	2	3	1	0.9864	0.9330	1.0248	0.933
17	2	3	2	0.9028	0.8493	0.9411	
18	2	3	3	0.8944	0.8410	0.9328	
19	3	1	1	1.0854	1.0320	1.1238	
20	3	1	2	1.0018	0.9483	1.0401	
21	3	1	3	0.9934	0.9400	1.0318	0.943
22	3	2	1	1.0948	1.0413	1.1331	1.133
23	3	2	2	1.0111	0.9577	1.0494	
24	3	2	3	1.0028	0.9493	1.0411	
25	3	3	1	1.0614	1.0080	1.0998	
26	3	3	2	0.9778	0.9243	1.0161	0.993
27	3	3	3	0.9694	0.9160	1.0078	

Table-V: Estimates of tensile load, T_L (kN) from empirical relation (3)

S. No.	Process parameters			Tensile load, T_L (kN)			
	A (W)	B (mm/sec)	C (mm)	Eq. (3)	Lower Bound	Upper Bound	Test [11]
1	2000	90	0	1.0228	0.9693	1.0611	1.038
2	2000	90	-1	0.9391	0.8857	0.9774	
3	2000	90	-2	0.9308	0.8773	0.9691	
4	2000	100	0	1.0321	0.9787	1.0704	
5	2000	100	-1	0.9484	0.8950	0.9868	0.895
6	2000	100	-2	0.9401	0.8867	0.9784	
7	2000	110	0	0.9988	0.9453	1.0371	
8	2000	110	-1	0.9151	0.8617	0.9534	
9	2000	110	-2	0.9068	0.8533	0.9451	0.945
10	2500	90	0	1.0104	0.9570	1.0488	
11	2500	90	-1	0.9268	0.8733	0.9651	0.965
12	2500	90	-2	0.9184	0.8650	0.9568	
13	2500	100	0	1.0198	0.9663	1.0581	
14	2500	100	-1	0.9361	0.8827	0.9744	
15	2500	100	-2	0.9278	0.8743	0.9661	0.943
16	2500	110	0	0.9864	0.9330	1.0248	0.933
17	2500	110	-1	0.9028	0.8493	0.9411	
18	2500	110	-2	0.8944	0.8410	0.9328	
19	3000	90	0	1.0854	1.0320	1.1238	
20	3000	90	-1	1.0018	0.9483	1.0401	
21	3000	90	-2	0.9934	0.9400	1.0318	0.943
22	3000	100	0	1.0948	1.0413	1.1331	1.133
23	3000	100	-1	1.0111	0.9577	1.0494	
24	3000	100	-2	1.0028	0.9493	1.0411	
25	3000	110	0	1.0614	1.0080	1.0998	
26	3000	110	-1	0.9778	0.9243	1.0161	0.993
27	3000	110	-2	0.9694	0.9160	1.0078	

IV. CONCLUDING REMARKS

This paper presents optimal process parameters to achieve maximum tensile load bearing capacity of laser weld thin galvanized steel sheets following the concepts of a modified Taguchi design of experiments. Excepted range of the tensile load bearing capacity is provided for the full factorial design of experiments. Empirical relation is developed and validated the tensile load bearing capacity in terms of the laser process parameters (viz., laser power, welding speed and focal point position). For the maximum value of T_L, the optimal process parameters from the ANOVA table are $A_3B_2C_1$ .Subscript denotes the level of the process parameter. The set of optimal process parameters are: laser power, A=3000 W; welding speed, B=100 mm/sec; and pocal point position, C=0 mm. For these process parameters, the expected range of T_L is from 1.0413 to 1.1331 kN, which confirms the test results of the test run-8 in Table-1. The microstructural examination on the optimally processed sample reveals fusion zone (FZ), heat affected zone (HAZ) and base metal (BM). The sample has highest hardness value in FZ. Taguchi approach is quite simple, straight forward and reliable in solving complex industrial optimization problems. Application of S/N ratio transformation to a single output response in [9] has no added advantage.

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