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OPTIMIZATION OF LASER BEAM WELDING OF STAINLESS STEELS IN OVERLAP JOINT CONFIGURATION

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ABSTRACT
This paper presents experimental design approach to process parameter optimization for laser welding of martensitic AISI416 and AISI440FSe stainless steels in a constrained overlap configuration. To determine the optimal laser-welding parameters, a set of mathematical models were developed relating welding parameters to each of the selected weld characteristics. Both the statistical and the experimental validations for the models were confirmed. The weld quality criterion considered determining optimal parameters was the maximization of weld penetration depth and resistance length. Laser power and welding speed in the range of 855-930W and 4.50-4.65 m/min respectively with a fiber diameter of 300μm were identified as the optimal set of process parameters. However, reducing the laser power in the range 800-840W and increasing the welding speed in the range 4.75-5.37 m/min caused stronger and better welds.

Keywords: Optimization, Laser Welding, Constrained Overlap Joint, Full Factorial Design (FFD).

1. INTRODUCTION
Laser welding is a high-energy-density welding process and well known for its deep penetration, high speed, small heat-affected zone, superior welding seam quality, low heat input per unit volume, and fiber optic beam delivery[1]. It is increasingly utilized in all industrial sectors like automobile, shipbuilding, electronic industry, etc. Nowadays, in automotive industries, manufacture of modern fuel injectors for gasoline, diesel, and gaseous fuels include laser welding to improve quality and maximize production throughput. Of the lasers used to weld the small, heat sensitive, complex parts of a fuel injector in automotive industries, continuous wave (CW) Nd:YAG laser performs best for welding, because of its short time cycles and metallurgy of the stainless steels used. Laser beam welding involves many variables; laser power, welding speed, focus diameter, defocus distance, beam incident angle, and shielding gas, any of which may have a significant influence on heat and fluid flows in the weld pool. These heat and fluid flows in the weld pool significantly affect the temperature gradients, the cooling rates, and the solidification structure of fusion and heat-affected zones and thus control penetration and profile of the fusion zone[2]. Since shape and microstructure of the fusion zone determine the properties of the weld, the combination of laser output power, welding speed, focal spot diameter, shielding gas and position accuracy should be selected accurately to get an acceptable quality welded joint ensuring desired weld-bead geometry, excellent mechanical properties with minimum distortion[3].

However, the main challenge for the manufacturer is how to choose the process input parameters that would provide an excellent welded joint with the required weld-bead geometry and weld quality with minimal adverse residual stresses and distortion. In order to predict the welding parameters accurately without consuming time, materials, and labor effort, different optimization methods are applied to specify the desired output variables through developing mathematical models [4-6]. This study, therefore, focuses on:

- development of mathematical models linking the laser welding input parameters (laser power, welding speed, and focal spot diameter) and each of the output responses (weld penetration depth, and resistance length) using full factorial design (FFD),
- statistical and experimental validations of the developed models, and
- finally, determination of optimal range of welding parameters that maximize the weld penetration depth, and resistance length.

2. EXPERIMENTAL
2.1 Material
The selected inner and outer shells of the fuel injector are made of martensitic AISI 440FSe and AISI 416 stainless steels respectively. These shells are circular welded to form an overlap joint. This joint is selected based on both technical and economical aspects, because they can provide satisfactory service performance and substantial savings. Moreover, in automotive industries, these materials are often used in welded form for making different types of fuel injectors. The weld seam characteristics are shown in Fig. 1. The inside diameter of the outer tube and the outside diameter of the inner

tube are machined to Ø7.5±0.025 mm and Ø7.458±0.015 mm respectively to obtain a clearance between the parts when assembled. Inner and outer shells are first assembled and crimped applying a uniform force of 12 kN around the tip of the outer shell, which is a replication of existing fabrication process.

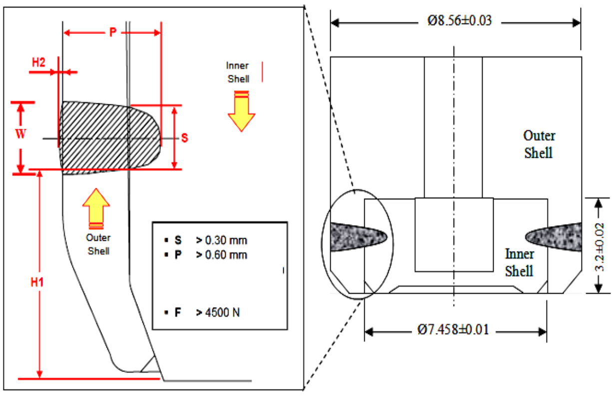

Fig 1. Characterization of welding cross-section (W: Weld width, P: Weld penetration depth, S: Weld resistance length).

2.2 Experimental Design

General full factorial design with replication is planned to conduct the experiments. The statistical software Design-Expert V7 is used to create the design matrix and analyze the experimental data. The laser-welding input variables are laser power (LP); welding speed (WS); and fiber diameter (FD). In order to find out the range of each process input parameter, initial test runs are carried out by changing one of the process parameters whilst keeping the rest of them at constant values. The weld quality requirements stated in ISO 13919-1 i.e. absence of detectable defects, size and location of weld spatter formed, and smooth appearance of welded surface are the criteria for selecting the working ranges. Table 1 shows main input factors, their corresponding coded and actual levels, and response factors considered.

Table 1: Experimental Conditions and Response Factors

Process Factors	Symbols	Levels of each factor: 1	2	3
Laser power (W)	LP	800	950	1100
Welding speed (m/min)	WS	4.5	6.0	7.5
Fiber Diameter (µm)	FD	300	-	400
Constant Factors				
Base material	: Outer Shell	: AISI 416		
	Inner Shell	: AISI 440 FSe		
Laser source	: Nd:YAG Laser			
Angle of Incidence (deg)	: 90^0 (onto the surface)			
Shielding gas	: Type	: Argon		
	Flow rate	: 29 l/min		
Response Factors				
Weld bead characteristics	: Weld Resistance Length (S), and Weld Penetration Depth (P)			

This statistical design of experiment (DOE) method is used to develop mathematical models relating the welding parameters to each of the selected weld characteristic length (weld resistance length, and penetration depth). The adequacy of the models developed and their significant linear and interaction model terms are confirmed by analyzing the variance and other adequacy measures. Finally, these mathematical models are used to determine the optimal settings of welding parameters to ensure the desired weld quality. In this study, the weld quality criterion applied to determine the optimal settings of welding parameters is the maximization of weld penetration depth, and weld resistance length.

2.3 Mechanical Characterization

Welding tests are carried out in a random order to avoid any systematic error in the experiment. After welding, transverse sections are prepared by cutting the samples axially using SampleMet II (Beuhler, IL) model abrasive cutter. The sectioned samples are mounted, polished, and etched for mechanical characterization. Software, Leica IM500, incorporated with an optical microscope (Leica MZ125) is used to measure weld resistance length, and penetration depth. Each set of experiments is replicated three times to ensure statistical accuracy. The mean value of each measured response parameter is determined and recorded for further analysis. Table 2 shows the average measured responses for various laser-welding conditions.

Table 2: Design matrix with actual process variables and response values

Std Order	Run Order	Actual levels: Laser Power, LP (W)	Welding Speed, WS (m/min)	Fiber Diameter, FD (µm)	Response Values: Penetration Depth, P (µm)	Resistance Width, S (µm)
1	14	800	4.50	300	960	440
2	7	950	4.50	300	1290	480
3	2	1100	4.50	300	1610	500
4	16	800	6.00	300	710	370
5	12	950	6.00	300	950	470
6	3	1100	6.00	300	1180	450
7	4	800	7.50	300	560	210
8	8	950	7.50	300	730	390
9	6	1100	7.50	300	880	510
10	18	800	4.50	400	790	529
11	10	950	4.50	400	1043	586
12	9	1100	4.50	400	1307	613
13	15	800	6.00	400	577	266
14	13	950	6.00	400	727	481
15	17	1100	6.00	400	920	588
16	11	800	7.50	400	492	33
17	5	950	7.50	400	580	273
18	1	1100	7.50	400	749	442

2.4 Optimization Procedure

The optimization module in Design-Expert software V7 searches for a combination of factor levels that simultaneously satisfy the requirements placed (i.e. optimization criteria) on each of the responses and process input factors (i.e. multiple-response optimization). Numerical optimization method is used in this work by selecting the desired goals for each factor and response. The numerical optimization process involves combining the goals into an overall desirability function (D). The numerical optimization feature in the design-expert package finds one point or more in the factors domain that maximizes this objective function.

3. RESULTS AND DISCUSSION

3.1 Statistical Model Development

At this stage, the fit summary in the design-expert software is used to determine the models that best describe the response factors. The fit summary includes sequential model sum squares to select the highest order polynomial, where additional terms are significant, and the model is not aliased. In addition, model summary statistics of the fit summary focuses on the model that maximizes adjusted R-squared and predicted R-squared values. Using the same statistical software package, the sequential F-test is carried out to find out if the regression model is significant and the significant model terms of the developed models. The stepwise regression method is also applied to eliminate the trivial model terms automatically.

3.1.1 Response Model Selection

Suitable response models for the response factors are selected based on the fit summaries. From fit summary output of the measured responses shown in Tables 3.1 – 3.4, it is clear that two-factor interaction (2FI) models are statistically acceptable for all the selected response factors and can be used for further analyses.

Table 3.1: Sequential model sum of squares for weld penetration depth

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Mean	1.432E+007	1	1.432E+007			
Linear	1.457E+006	3	4.855E+005	77.15	< 0.0001	
2FI	63735.88	3	21245.29	9.59	0.0021	Suggested
Quadratic	21029.47	2	10514.74	28.35	0.0001	Aliased
Cubic	2930.23	5	586.05	5.74	0.0576	Aliased
Residual	408.15	4	102.04			
Total	1.586E+007	18	8.814E+005			

Table 3.2: Model summary statistics for penetration depth model

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	79.33	0.9430	0.9307	0.8974	1.585E+005	
2FI	47.07	0.9842	0.9756	0.9559	68167.91	Suggested
Quadratic	19.26	0.9978	0.9959	0.9893	16565.79	Aliased
Cubic	10.10	0.9997	0.9989	0.9906	14486.37	Aliased

Table 3.3: Sequential model sum of squares for weld resistance length

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Mean	3.235E+006	1	3.235E+006			
Linear	2.699E+005	3	89952.05	12.21	0.0003	
2FI	88819.20	3	29606.40	22.70	< 0.0001	Suggested
Quadratic	6286.94	2	3143.47	3.51	0.0746	Aliased
Cubic	1831.13	5	366.23	0.24	0.9279	Aliased
Residual	6228.19	4	1557.05			
Total	3.608E+006	18	2.005E+005			

Table 3.4: Model summary statistics for weld resistance length model

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	85.84	0.7234	0.6642	0.5075	1.837E+005	
2FI	36.11	0.9615	0.9406	0.8934	39781.76	Suggested
Quadratic	29.92	0.9784	0.9592	0.9036	35941.38	Aliased
Cubic	39.46	0.9833	0.9290	0.4591	2.018E+005	Aliased

3.1.2 Analysis of Variance (ANOVA)

The tests for significance of the regression models and on individual model coefficient are performed using the same statistical package. By selecting the stepwise regression method that eliminates the trivial model terms automatically, the resulted ANOVA Tables 3.5 and 3.6 for the selected models summarize the analysis of variance of each response, and determine its significant model terms. The aforesaid tables show that calculated Fisher's 'Model-F' and 'Model-P' values are respectively 114.39 & <0.0001 for weld penetration depth model; and 45.83 & <0.0001 for weld resistance length model. These 'Model-F' and 'Model-P' values indicate that the selected models are highly significant, and there is only a less than 0.01% chance that these large 'Model-F' values could occur due to noise. The associated P values of less than 0.05 for the models (i.e. α = 0.05, or 95% confidence level) indicate that the models are statistically significant [7].

Table 3.5: ANOVA table for weld penetration depth 2FI model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1.520E+006	6	2.534E+005	114.39	< 0.0001	significant
LP	5.447E+005	1	5.447E+005	245.89	< 0.0001	
WS	7.542E+005	1	7.542E+005	340.44	< 0.0001	
FD	1.577E+005	1	1.577E+005	71.20	< 0.0001	
LP-WS	43512.50	1	43512.50	19.64	0.0010	
LP-FD	8712.04	1	8712.04	3.93	0.0729	
WS-FD	11511.34	1	11511.34	5.20	0.0436	
Residual	24367.85	11	2215.26			
Cor Total	1.545E+006	17				
R^2 = 0.9842	Adj. R^2 = 0.9756		Pred. R^2 = 0.9559		Adeq. Precision = 37.979	

Table 3.6: ANOVA table for weld resistance length 2FI model

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob > F	
Model	3.587E+005	6	59779.23	45.84	< 0.0001	significant
LP	1.314E+005	1	1.314E+005	100.74	< 0.0001	
WS	1.385E+005	1	1.385E+005	106.16	< 0.0001	
FD	4.50	1	4.50	3.450E-003	0.9542	
LP-WS	39762.00	1	39762.00	30.49	0.0002	
LP-FD	11760.45	1	11760.45	9.02	0.0120	
WS-FD	37296.75	1	37296.75	28.60	0.0002	
Residual	14346.26	11	1304.21			
Cor Total	3.730E+005	17				
R^2 = 0.9615	Adj. R^2 = 0.9406		Pred. R^2 = 0.8934		Adeq. Precision = 26.563	

The same ANOVA tables show the other adequacy measures e.g. R-squared, adjusted R-squared, and predicted R-squared values. All these measures are in logical agreement and demonstrate significant relationships. Moreover, adequate precision compares range of predicted value at the design points to average prediction error. The adequate precision ratios in all cases are dramatically greater than four indicating adequate models discrimination.

Again, the ANOVA table for the weld penetration depth model shows that linear terms of laser power (LP), welding speed (WS), and fiber diameter (FD) and two-factor interactions (2FI) of laser power-welding speed (LP-WS), and welding speed-fiber diameter (WS-FD) are the significant model terms associated with the weld penetration depth. Nonetheless, linear terms such as laser power (LP), welding speed (WS), and fiber diameter (FD) have the most significant effects on the weld penetration depth. For the weld resistance length model, ANOVA table demonstrates that linear terms such as laser power (LP), and welding speed (WS) and all the two-factor interactions (2FI) i.e. laser power-welding speed (LP-WS), welding speed-fiber diameter (WS-FD), and laser power-fiber diameter (LP-FD) are significant model terms. However, linear term of fiber diameter is added to support hierarchy of weld resistance length model. It is worthmentioning that the parametric effects on the selected response factors have been analyzed in detail elsewhere [8].

Moreover, a positive sign of the coefficient represents a synergistic effect, while a negative sign indicates an antagonistic effect. From the tables, linear term laser power and the interaction term like welding speed-fiber diameter have a positive relationship with weld penetration depth; linear parameter laser power and its interactions with welding speed and fiber diameter affect positively on weld resistance length. These abovementioned synergistic effects demonstrate that their corresponding response factors will increase with an increase in aforestated factors; otherwise, decreases.

The previously mentioned analyses show that the statistical models for predicting the weld penetration depth and the weld resistance length can be of the following forms:

i. Weld penetration Depth

$$P = -995.0 + 4.64\,LP - 0.28\,WS - 0.94\,FD - 0.33\,LP \times WS - 3.6E\text{-}003\,LP \times FD + 0.42WS \times FD$$

ii. Weld resistance length

$$S = 1807.2778 - 2.64333LP - 109.11111\,WS + 0.48463\,FD + 0.31333LP \times WS + 4.17407E\text{-}003\,LP \times FD - 0.74333\,WS \times FD$$

3.2 Validation of the Models

3.2.1 Normality Test for Residuals

The normal probability plot indicates whether the residuals follow a normal distribution, in which case the points will follow a straight line. Figs 3.1(a)-(b) illustrate the normal probability plots of residual values for weld penetration depth and resistance length. The figures show that the points on the plot fall fairly close to the straight line. This is an implication that the empirical distribution of residual data is well compared with a normal distribution having the same mean and variance.

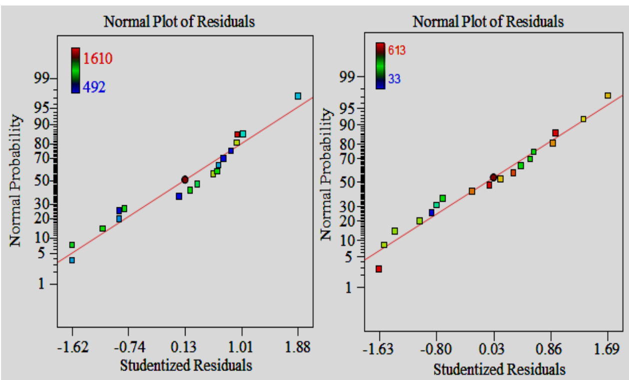

Fig 3.1. Normal probability plot for (a) weld penetration depth and (b) weld resistance length

3.2.2 Test for Randomness of Residuals

To verify the randomness of the data, studentized residuals versus fitted data has been plotted for weld penetration depth and resistance length as shown in the Figs 3.2(a) and (b) respectively. The figures present that the residuals are scattered randomly about zero. This random dispersion of the residual data indicates that the errors have a constant variance for all response variables.

Plot of standardized residuals vs. predicted values also shows the possible existence of outliers. If a point lies far from the majority of points, it may be an outlier. It is essential to identify the outliers as these can significantly influence the model and provide potentially misleading or incorrect results. As shown in the figures, all the points are within ± 2.0σ limits for each of the response models and confirm no existence of such outliers.

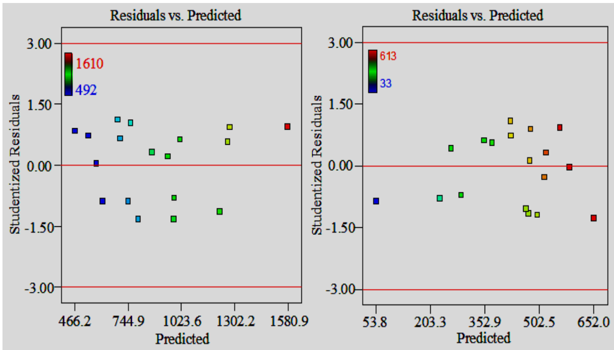

Fig 3.2. Studentized residual versus predicted plot for (a) weld penetration depth and (b) weld resistance length

3.2.3 Experimental Validation

Three validation experiments are also conducted with welding conditions chosen randomly within the ranges for which the equations are developed. The actual results are calculated as the average of three measured results for each response. The actual results, predicted values, and calculated percentage error of confirmation experiments are given in Table 3.5. From the validation experiments, it is observed that there is a small percentage error between the estimated and the experimental values. These results indicate that the statistical models can provide nearly accurate results.

Table 3.5: Confirmation experiments

No. of Expt	Process Parameters				Response Factors	
	LP (W)	WS (m/min)	FD (μm)		Penetration Depth (μm)	Resistance (μm)
				Actual	840	450
Expt. I	1000	7.0	300	Predicted	853.04	430.097
				Error(%)	**-1.53**	**4.4**
				Actual	634	317
Expt. II	900	6.5	400	Predicted	668.68	315.9
				Error(%)	**-5.47**	**3.47**
				Actual	939	454
Expt. III	850	5.0	300	Predicted	975.1	441.3
				Error(%)	**-3.84**	**2.79**

3.3 Process Parameter Optimization

From weld design guidelines as described in ISO15614-11, weld penetration depth and resistance length are the response factors that characterize an overlap welded joint. Laser welding input parameters should be optimized to achieve the optimal values of these response factors. Two sets of criteria are implemented in the numerical optimization. The first set of criteria is to get maximum penetration depth and resistance length of the weld with no limitation on the process parameters. For this joint, reducing the laser power and increasing the welding speed are the most common techniques used to produce relatively low-cost and excellent weld joints. Taking the cost and quality aspects into account second set of criteria are fixed to maximize welding speed and minimize laser power along with former goals. Table 3.6 summarizes these two criteria, lower and upper limits, as well as importance for each input and response factor.

Table 3.6: Optimization criteria used in this study

Parameters or Responses	Limits		Importance	Criterion	
	Lower	Upper		First	Second
Laser Power(W)	800	1100	3	is in range	minimize
Welding Speed(m/min)	4.5	7.5	3	is in range	maximize
Fiber Diameter(µm)	300	400	3	is in range	is in range
WZ Width(µm)	460	500	5	is in range	minimize
Weld Penetration Depth(µm)	600	1200	5	maximize	maximize
Weld Resistance lentgh(µm)	300	600	5	maximize	maximize

Tables 3.7 and 3.8 show the optimal solution based on two optimization criteria as determined by design-expert software. The results demonstrate that, whatever the optimization criteria, the fiber diameter has to be 300µm to obtain a weld with deeper weld penetration, and longer weld resistance.

Table 3.7: optimal solutions as obtained based on first criterion

Solution Number	Laser power (W)	Welding Speed (m/min)	Fiber Diameter (µm)	Weld Penetration Depth (µm)	Weld Resistance (µm)
1	920.52	4.50	302.30	1200.06	475.773
2	926.36	4.50	301.08	1215.16	476.755
3	927.61	4.50	300.82	1218.41	476.519
4	931.48	4.50	300.01	1228.46	477.816
5	919.99	4.50	301.59	1200.00	476.938
6	924.44	4.50	300.00	1213.76	475.628
7	922.22	4.53	301.41	1200.01	475.563
8	923.06	4.55	300.83	1200.01	474.264
9	913.08	4.50	300.00	1190.01	475.414
10	900.07	4.50	300.00	1162.78	475.168
11	898.64	4.50	300.00	1159.80	475.141
12	917.47	4.65	300.00	1172.68	468.817
13	884.79	4.50	300.00	1130.82	474.88
14	855.00	4.50	300.00	1068.52	474.317

Table 3.8: optimal solutions as obtained based on second criterion

Solution Number	Laser power (W)	Welding Speed (m/min)	Fiber Diameter (µm)	Weld Penetration Depth (µm)	Weld Resistance (µm)
1	800.00	4.77	300.00	916.09	451.314
2	800.00	4.80	300.00	911.47	448.596
3	802.02	4.77	300.00	919.84	451.353
4	800.04	4.75	300.09	919.30	453.283
5	800.00	4.82	300.00	908.87	447.071
6	804.18	4.76	300.00	925.40	452.283
7	807.61	4.77	300.00	930.95	451.888
8	813.06	4.77	300.00	942.66	452.885
9	815.01	4.77	300.00	945.81	452.68
10	817.99	4.76	300.00	954.13	454.221
11	819.99	4.75	300.00	959.27	455
12	829.78	4.76	300.00	976.98	454.991
13	839.99	4.78	300.00	994.99	454.895
14	800.00	5.37	300.00	832.94	402.456

Table 3.7 shows that the largest obtainable weld penetration depth and resistance length are 1228µm, and 478µm respectively, and the associated laser power and welding speed are 932W and 4.5 m/min respectively. However, with an acceptable weld penetration depth and weld resistance length, the laser power can be minimized to its lowest value and the welding speed can be maximized to 5.37 m/min as shown in Table 3.8. Under this condition, the weld penetration depth and resistance length would be 833µm and 402µm respectively, which are much greater than the respective required values for this welded joint. Besides, any combination of process parameters for the second optimal settings causes less energy density input to the weld. This reduced energy input results in less distortion and formation of cracks, blowholes, and spatter, which lead to better weld quality as can be seen from visual inspection data given in Table 3.9.

Table 3.9: Visual inspection of weld quality

Process Parameters			Visual check		
Laser power	Welding Speed	Fiber Diameter	Cracks	Blow holes	Spatter
800	4.5	300	0	0	1
950	4.5	300	0	0	2
1100	4.5	300	0	0	2
800	6	300	0	0	1
950	6	300	1	0	2
1100	6	300	1	0	1
800	7.5	300	0	0	0
950	7.5	300	1	0	1
1100	7.5	300	1	0	1

4. CONCLUSIONS

For the laser system, weld joint type and the limits of laser parameters considered in this study, the following points can be concluded:

1. Full factorial design can be used to optimize the laser welding process in order to obtain the most desirable weld quality in terms of weld bead geometry, and determine the corresponding optimal settings of welding parameters.
2. Laser power and welding speed are the most influential factors affecting the selected weld bead characteristics, and fiber diameter has little effect on them.
3. A laser power and welding speed in the range of

800-840W and 4.75-5.37 m/min respectively with fiber diameter of 300μm are the optimal settings of welding parameters to achiece an excellent welded component made of martensitic stainless steels AISI416 and AISI 440Se.

4. Strong and efficient weld joints could be achieved using the welding conditions obtained from the numerical optimization.

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7. MAILING ADDRESS

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