

# Laser Welding Process Parameters Optimization Using Variable-Fidelity Metamodel and NSGA-II

Chaochao Wang, Qi Zhou, Ping Jiang, Leshi Shu and Xiongbing Li

*The State Key Lab of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China*

**Abstract.** An optimization methodology based on variable-fidelity (VF) metamodels and nondominated sorting genetic algorithm II (NSGA-II) for laser bead-on-plate welding of stainless steel 316L is presented. The relationships between input process parameters (laser power, welding speed and laser focal position) and output responses (weld width and weld depth) are constructed by VF metamodels. In VF metamodels, the information from two levels fidelity models are integrated, in which the low-fidelity model (LF) is finite element simulation model that is used to capture the general trend of the metamodels, and high-fidelity (HF) model which from physical experiments is used to ensure the accuracy of metamodels. The accuracy of the VF metamodel is verified by actual experiments. To solve the optimization problem, NSGA-II is used to search for multi-objective Pareto optimal solutions. The results of verification experiments show that the obtained optimal parameters are effective and reliable.

## 1 Introduction

Laser welding has been widely used in a variety of industrial applications due to its significant advantages including deep penetration, narrow heat-affected zone. It is very important to determine process parameters that are highly relevant to impact welding bead profile. Generally, a promising strategy is to utilize metamodels fitting the relationships between the input process parameters and the output responses for the sake of optimal welding bead in the laser welding process parameters optimization.

In the broadest sense, metamodel assisted process parameters optimization methods can be divided into two distinct types: physical experiment-based optimization approach and simulation-based optimization approach. Physical experiment-based optimization approach obtains the data for constructing the metamodel by conducting laser welding experiments [1-4]. The main shortcoming of this method is that it requires a significant time and economic costs to ensure the accuracy of the metamodel. Simulation-based optimization approach, on the other hand, obtains the bead profile by running computational simulation models [5-7]. Compared with the physical experiment-based optimization approach, the most obvious advantage is that it can greatly shorten the design period and reduce the overall cost. However, this approach is difficult to ensure the accuracy of metamodel. This issue, to some extent, has limited their capability of guiding the actual laser welding processing.

To overcome the above mentioned shortcomings, this paper proposes an optimization methodology based on variable-fidelity (VF) metamodel [8, 9], which is able to

combine the information from two different levels fidelity models, low-fidelity (LF) simulation model and high-fidelity (HF) physical experiment, for laser welding process parameter optimization. In the proposed VF metamodels approach, the LF simulation model is a three-dimensional thermal finite element (FE) model that is used to capture the general trend of the metamodels and the HF model which from physical experiments is used to ensure the accuracy of metamodels. The two levels fidelity models are integrated into VF metamodels using the method of Hierarchical-Kriging (HK) [10]. The constructed VF metamodels will be used to describe the relationship between process parameters and welding bead profile. In optimization process, the nondominated sorting genetic algorithm II (NSGA-II) is adopted to facilitate design space exploration and multi-objective Pareto optimal search [11]. The proposed methodology is applied to obtain optimum process parameters of the laser bead-on-plate welding for stainless steel 316L.

## 2 Optimization methodology

In this paper, the optimization methodology is proposed where HK metamodel is used to establish the VF metamodels between the process parameters and welding bead profiles; NSGA-II is used to facilitate design space exploration and global optimum search. The overall optimization process based on VF metamodels is depicted in the flowchart of Figure 1. The details steps are as follows:

**Step 1** Determine the laser welding process parameters optimization problem including the target function, the amount of parameters and parameter ranges.

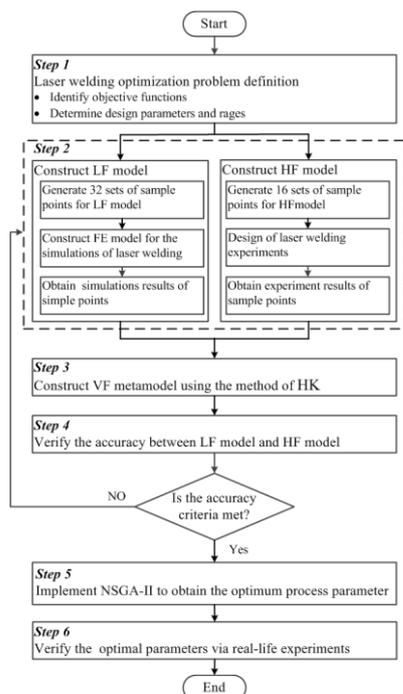
**Step 2** Construct LF simulation model and HF physical experiment model to investigate the relationship between process parameters and welding bead profile.

**Step 3** Construct VF metamodells using the method of HK metamodel.

**Step 4** Check whether the accuracy of the constructed VFM. If yes, go to next step, otherwise, adjust the LF model.

**Step 5** Implement NSGA-II to obtain the optimum process parameters according to the prediction function of the constructed VF metamodells.

**Step 6** Verify optimal results through experiments.

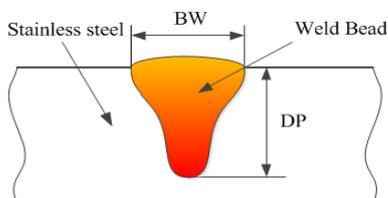


**Figure 1.** Flowchart of the proposed approach.

The goal of optimization problem is to solve the nonlinear task of the form as blow:

$$\begin{aligned}
 &\text{Objective: Minimize BW} \\
 &\quad \text{Maximize DP} \\
 &\text{Subject to: } 2.0 \leq LP \leq 3.5 \\
 &\quad 2.5 \leq WS \leq 3.5 \\
 &\quad -2.0 \leq LF \leq 0
 \end{aligned} \tag{1}$$

where the input variables include laser power (LW), welding speed (WS) and laser focal position (LF). The output parameters are depth of penetration (DP) and bead



**Figure 2.** schematic of welding bead profile.

width (BW), as shown in Figure 2. The objective is to obtain the maximized DP and minimized BW. The two objectives and the optimization problem in equation (1) are trade-offs for a multi-objective optimization problem.

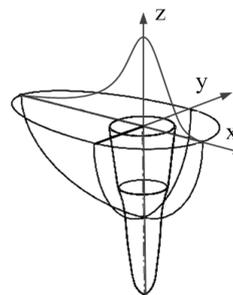
### 3 VF metamodel construction

#### 3.1 Construct LF simulation model

In this study, a three-dimensional thermal FE model is developed to simulate the bead profile in laser welding process. Due to complex changes in the actual welding process, simplifying assumptions are made as follows [12, 13]:

- The initial temperature of the weldment is 300K.
- The finite element model is heat conduction model, which the formation of keyhole is not considered.
- The thermal transfer of weldment is of solid-solid, and there is no chemical reaction, agitation or oxidation in the melt pool.

The half of weldment by the centerline of welding bead is taken to construct FE model using ICEM CFD 14.0 software. The computational domain of model has a dimension of 6\*4\*3(mm). The size of mesh is 0.1mm and consists of 66,729 elements.



**Figure 3.** Heat source model.

The most commonly used heat sources of laser welding simulation have a Gaussian distribution [14]. In this study, the body heat source model combined by double-ellipsoids and rotating-Gaussian is developed for FE simulation, shown in Figure 3.

**Table 1.** Thermal properties of stainless steel 316L.

Thermal properties	Value
Density ( $g / cm^3$ )	7.91
Solid temperature (K)	1616
Liquid temperature (K)	1718

**Table 2.** Temperature dependent thermal properties of stainless steel 316L.

Temperature (K)	Conductivity ( $W/m \cdot K$ )	Specific Heat ( $J/G \cdot K$ )
300	15.91	0.45
800	22.46	0.66
1300	29.01	0.65
1616	33.15	0.79
1660	33.67	1.12
1718	30.62	0.78
2000	35.07	0.79
2500	42.95	0.81
3000	50.83	0.83

The physical properties parameters of the stainless steel 316L are shown in Table 1. The specific heat capacity and thermal conductivity change with temperature, calculated by JMatPro software, are shown in Table 2.

The FE simulation for laser welding process is calculated by FLUENT 13.0 software which about 16.5 hours was totally spent for computation. 32 sets of sample points were obtained by the method of optimal Latin hypercube [15], and these sample points were employed to obtain the simulation results of welding bead profile, namely the LF model data. Figure 4 shows the transient temperature contours of laser welding process at 5ms. Figure 4(a) shows the whole three-dimensional transient temperature contours by mirror symmetry; Figure 4(b) shows whole isothermal surface with temperature above the fusion temperature ( $T > 1616K$ ) by mirror symmetry; Figure 4(c) shows isothermal surface with all temperatures of half model; Figure 4(d) shows the temperature contours at the cross section of welding bead.

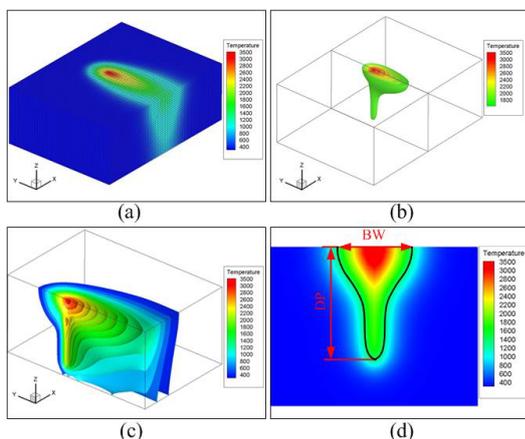


Figure 4. Transient temperature contours after 5ms.

### 3.2 Design HF physical experiment

In this paper, the data of HF model is from laser welding physical experiments. Figure 5 demonstrates the laser welding equipment used in this study. The laser welder is IPG YLR-4000 ytterbium-doped fiber laser. Laser is delivered through the optical fiber to the laser welder head. The laser welding header is installed on the robot ABB IRB4400.

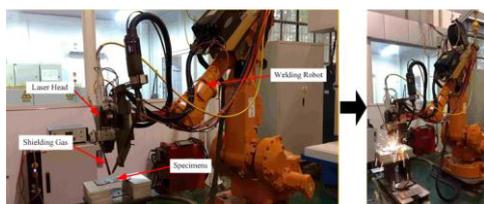


Figure 5. Laser welding equipment.

16 set of sample points are generated by the method of optimal Latin hypercube. Then, the experiment results of sample points are obtained through the designed experiments. As shown in Figure 6, the two outputs of welding bead profile were observed on optical microscope and measured with measurement software

CSM1 according to the transverse section of each weldment.

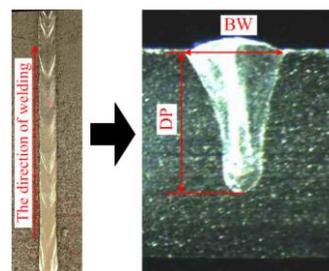


Figure 6. Experiment results after post processing.

### 3.3 Construct HK metamodel

In this paper, the VF metamodels are constructed by the method of HK. We can get the HK predictor that can be written in a form as:

$$\hat{y}(x) = \beta_0 \hat{y}_f(x) + r^T(x) \underbrace{R^{-1}(y_s - \beta_0 F)}_{=V_{HK}} \quad (2)$$

where  $\hat{y}_f(x)$  is low-fidelity model.  $\beta_0$  is a scaling factor indicating how much the low-fidelity and high-fidelity functions are correlated to each other, and it is calculated only by the initial sample points.

The LF models and HF models are integrated into VF metamodels using the HK metamodel. The constructed VF metamodels can describe the relationship between process parameters and welding bead profile. As shown in Figure 7, the constructed VF metamodels for BW and DP are demonstrated.

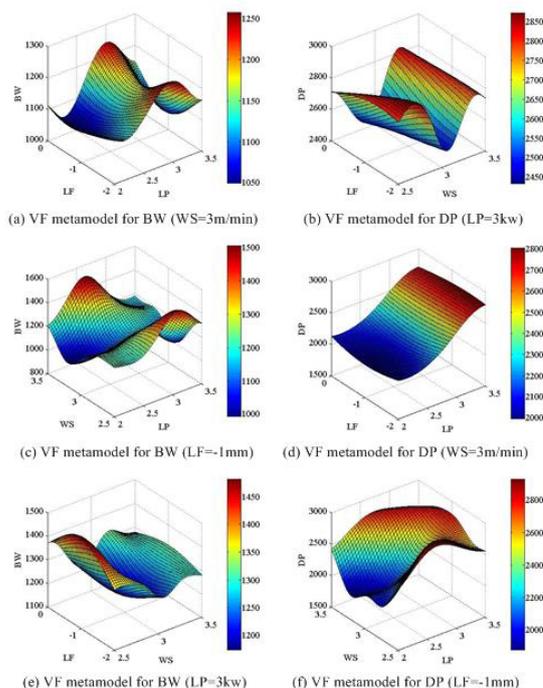
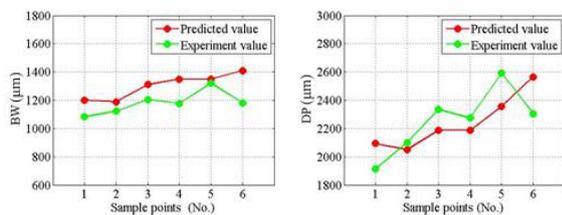


Figure 7. VF metamodels for BW and DP.

### 3.4 Verify the variable-fidelity metamodel

6 sets of sample points (NO.1-6) are randomly selected to verify the accuracy of VF metamodells by laser welding experiments. Comparison of predicted values and simulated values is shown in Figure 8. There has a good agreement between predicted values and experiment values. Table 3 demonstrates the predicted results of VF metamodells. The average relative error of VF metamodells for BW and DP are 9.11% and 7.00%. Therefore, the constructed VF metamodells are reliable and can be used for predicting welding bead profile in optimization section.



**Figure 8.** Comparison of predicted values and experiment values.

**Table 3.** Predicted results of VF metamodells.

No.	LP	WS	LF	Relative error (%)	
				BW	DP
1	2.10	3.00	-1	9.86	8.56
2	2.10	3.00	-2	5.42	2.45
3	2.18	2.68	-2	8.16	6.78
4	2.40	2.83	-2	12.80	4.04
5	2.63	3.34	-1	2.15	10.06
6	2.58	2.88	-2	16.25	10.13
Average error:				<b>9.11</b>	<b>7.00</b>

## 4 Optimization of laser welding process parameters

### 4.1 Multi-objective optimization using NSGA-II

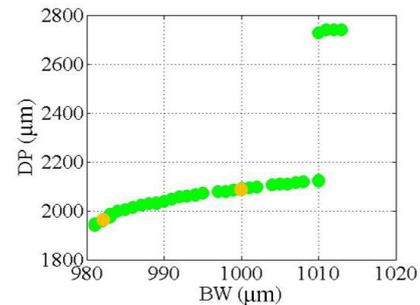
NSGA-II is implemented to solve the laser welding process parameters optimization problem and obtain the Pareto-optimal front. The settings for the NSGA-II in this two objective optimization problem are listed in Table 4. Fitness values of BW and DP in NSGA-II optimization process are predicted by VF metamodells constructed in the previous steps.

**Table 4.** Settings of NSGA-II parameters.

Parameter	Value
Population size	40
Maximum iterations	300
Elite count	2
Pareto fraction	0.4
Crossover fraction	0.8
Mutation fraction	0.2
Function tolerance	10E-06
Scaling fitness function	Rank

Figure 9 plots the obtained Pareto-optimal front for BW and DP. Each point illustrates a specific optimal

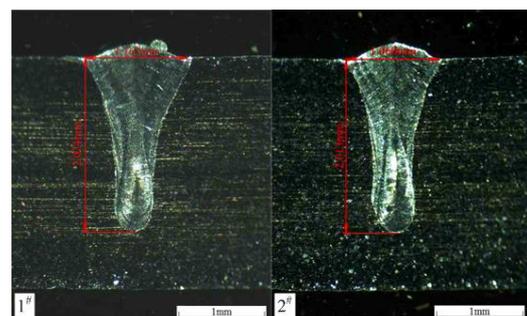
solution. It can be concluded from Figure 9 that all optima are non-inferior with each other because there are trade-offs among the BW and DP.



**Figure 9.** Pareto-optimal front for BW and DP.

### 4.2. Verification experiments of optimal solution

Two solutions in the Pareto-optimal front are selected and carried out to verify the effectiveness of the optimal results. Figure 10 shows the welding bead profile and dimension of these three verification experiments. The optimal parameters and corresponding outputs responses are listed in Table 5. As illustrated in Table 5, the maximum relative error of BW is 14.16%. For DP, the maximum relative error is 3.13%. It can indicate that the prediction accuracy of proposed approach can meet the requirement of process parameters optimization.



**Figure 10.** Weld appearances and dimensions of welding cross-sections of optimal results.

**Table 5.** Results of the verification experiments.

No.	LP	WS	LF		BW	DP
1	3.50	2.91	-1	Optimized (µm)	1000	2088
				Experimental (µm)	1165	2024
				Relative error (%)	<b>14.16</b>	<b>3.07</b>
2	2.30	3.12	0	Optimized (µm)	982	1952
				Experimental (µm)	1060	2013
				Relative error (%)	<b>7.36</b>	<b>3.13</b>

In terms of the weld appearances, it can be observed in Figure 10 that the weld appearances of two optimal results are beautiful and few defects exist in the welding bead.

## 5 Conclusion

In this paper, an optimization methodology using VF metamodel and NSGA-II is proposed for process parameters optimization in laser bead-on-plate welding for stainless steel 316L. The proposed approach could

obtain the desired welding bead profile which can improve the quality of the welding bead remarkably. In addition, the verification experiments for VF metamodel and optimal results have been analyzed. It is obvious that the approach can provide a reliable guidance for laser welding experiments. Following conclusions can be drawn from the above investigation:

1. The predicted values of VF metamodels have agreement with experiment results. The VF metamodels could predict the welding bead profile with small error.
2. Verification experiments of obtained optimal process parameters have proved that the optimization results is in good agreement with experiments results.

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## References

1. Y Rong, Z Zhang, G Zhang, C Yue, Y Gu, Y Huang, et al, *Optics and Lasers in Engineering*, **67**, 94-104 (2015)
2. P Jiang, L Cao, Q Zhou, Z Gao, Y Rong, X Shao, *IJMAT*,(to be published) 2016
3. Q Zhou, P Jiang, X Shao, Z Gao, L Cao, C Yue, X Li, *Metallurgical and Materials Transactions B*, (to be published) 2016
4. Q Zhou, Y Rong, X Shao, P Jiang, Z Gao, L Cao, *Journal of Intelligent Manufacturing*, (to be published) 2016
5. X Wang, H Chen, H Liu, P Li, Z Yan, C Huang, et al. *Optics and Lasers in Engineering*, **51(11)**:1245-1254 (2013)
6. M.H. Shojaeefard, M Akbari, P. Asadi, *International Journal of Precision Engineering and Manufacturing*, **15(11)**: 2351-2356 (2014)
7. M. Islam, A. Buijck, M. Rais-Rohani, K. Motoyama, *Advances in Engineering Software*, **79**: 127-136 (2015)
8. Q Zhou, X Shao, P Jiang, L Cao, H Zhou, L Shu, *CMES*, **106(5)**: 323-355 (2015)
9. G. Sun, G. Li, M. Stone, Q. Li, *Computational Materials Science*, **49(3)**: 500-511 (2010)
10. Z-H Han, R Zimmermann, S Görtz, AIAA Paper, 1225: 2010(2010)
11. K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, IEEE Transactions on, **6(2)**: 182-197 (2002)
12. M.R.N. Esfahani, J. Coupland, S. Marimuthu, *Journal of Materials Processing Technology*, **224**: 135-142 (2015)
13. R. Wang, Y. Lei, Y. Shi, *Optics & Laser Technology*, **43(4)**: 870-873 (2011)
14. J. Goldak, A. Chakravarti, M. Bibby, *Metallurgical transactions B*, **15(2)**: 299-305 (1984)
15. J.-S. Park, *Journal of statistical planning and inference*, **39(1)**: 95-111 (1994)