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Research Paper

Robust optimization for reducing welding-induced angular distortion in fiber laser keyhole welding under process parameter uncertainty

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HIGHLIGHTS

- A robust optimization framework for reducing welding-induced distortion is proposed.
- A three-dimensional thermo-mechanical finite element model (FEM) is developed.
- The FEM is validated by laser welding experiments.
- The process parameter uncertainty is quantified.
- The reliability of the obtained robust optimum is verified by Monte Carlo method.

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ABSTRACT

Welding-induced angular distortion is a typical out-of-plane distortion, which brings negative effects on the joints' quality. Therefore, the selection of appropriate process parameters to minimize or control welding-induced distortion under uncertainty has become of critical importance. In this paper, a robust process parameter optimization framework is proposed to reduce welding-induced distortion in fiber laser keyhole welding under parameter uncertainty. Firstly, a three-dimensional thermal-mechanical finite element model (FEM) for simulating the welding-induced distortion is developed and validated by laser welding experiment. Secondly, a Gaussian process (GP) model is constructed to build the relationship between the input process parameters and output responses. Finally, uncertainty quantification of both process parameter uncertainty and GP model uncertainty is derived. The obtained uncertainty quantification formulas are used in the robust optimization problem to minimize welding-induced distortion. The effectiveness and reliability of the obtained robust optimum are verified by the Monte Carlo method.

1. Introduction

Laser welding (LW), as an advanced manufacturing technology, has been widely used in the aerospace, shipbuilding, energy, and automotive industries [1–3]. It has advantages over other joining technologies such as a high degree of automation, enhanced joint strength, high energy density, and a narrow heat-affected zone [4–7]. However, one of the major issues in laser welding is welding-induced distortion during the LW process, which significantly affects the quality of the welding joints, especially in mechanical strength and dimensional accuracy. Fig. 1 shows a schematic diagram of the laser keyhole welding process. Generally, the welding distortions are mainly caused by the changes of the temperature field of the welding pool during the welding process. The most severe one is the angular distortion, as illustrated in Fig. 2 (a). Therefore, additional post-weld treatments are usually required to correct the welding-induced distortions toward a satisfactory level of joint strength and dimensional accuracy [8]. Post-weld treatments are always time-consuming and costly, therefore only practical in the most critical applications. For industrial applications where the financial budget consideration is critical, the best practice is to actively control the welding-induced distortions during the welding process by selecting the optimum welding process parameters.

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Nomenclature

Abbreviations

BPNN	back propagation neural network
FCD	faces centered design
FEM	finite element method
GA	genetic algorithm
GP	Gaussian process
HSSD	Hammersley sequence sampling design
LFP	laser focal position
LP	laser power
LW	laser welding
MC	Monte Carlo
MLE	maximum likelihood estimate
OLHS	optimal Latin hypercube sampling
PI	prediction intervals
PSR	polynomial surface regression
P/W	the ratio of weld penetration to the width
RMAE	relative maximum absolute error
RMSE	root mean square error
SQP	sequential quadratic program
UD	uniform design
WS	welding speed

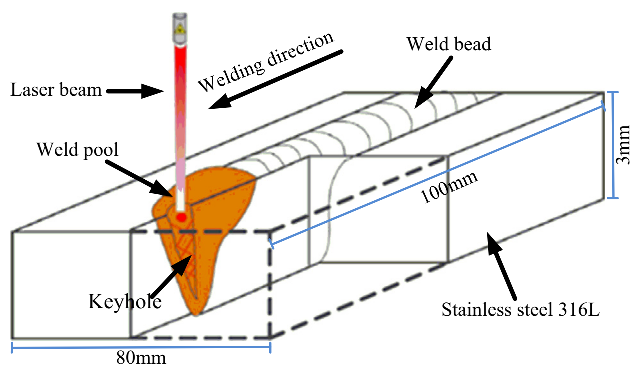

Fig. 1. Schematic plot of laser welding process.

Several welding process parameters, such as laser power, welding speed, laser focal position, contribute to the distortion [9,10]. Better control of the most influential process parameters will be most effective in eliminating the distortion. Most research on controlling welding-induced distortions has been done by conducting physical experiments [11–13]. In those efforts, a large number of experiments were conducted in a predefined process parameter domain to obtain the welding-induced distortions. Based on the experimental data, the process parameter values that can meet the final weld joint requirement will be chosen. This resource-consuming trial-and-error method often leads to sub-optimal solutions [8,14,15]. To improve the efficiency, the design of experiment and optimization approaches have been proposed [9,16,17]. In these approaches, laser welding experiments are only conducted at certain sample points. Metamodels are constructed to approximate the relationship between input process parameters and output welding-induced distortion. Metamodels are used in numerical optimization algorithms to predict the best parameter values. For example, Narwadkar and Bhosle [17] applied the Taguchi method to generate a three-level three-factor sampling plan. Then, the optimal input parameters were obtained. Although the design of experiment approaches help obtain the optimum process parameters, the required laser welding experiments for metamodeling are still time-consuming and costly because of the highly nonlinear and non-smooth relationships between input and output [8,10,18,19].

With the fast advancement of computer's capability and speed, computational simulation methods, e.g. finite element method (FEM), has made it possible to replace the physical experiments by simulating the thermo-mechanical behavior of structures during laser welding process. Several researchers have studied the problem of distortion through FEM in welding processes [18,20–25]. For example, Deng and Murakawa [18] developed a large deformation and thermo-elastic-plastic FEM for simulating welding distortion in a low-carbon steel butt-welded joint with a thickness of 1 mm. Wang et al. [24] employed an elastic FEM to simulate welding distortion in the fabrication of a cantilever beam component of a jack-up drilling rig; Manurung et al. [25] used a linear thermal elastic FEM to analyze the welding-induced distortion in combined butt and T-joints with 9-mm low carbon steel. It was concluded from these studies that FEM is a very powerful and reliable tool for modeling and analyzing welding processes. Nevertheless, limited research work has been conducted in integrating FEM in process optimization. Song et al. [26] successfully performed a welding residual stress minimization problem by adopting the Broyden–Fletcher–Goldfarb–Shanno (BFGS) line search

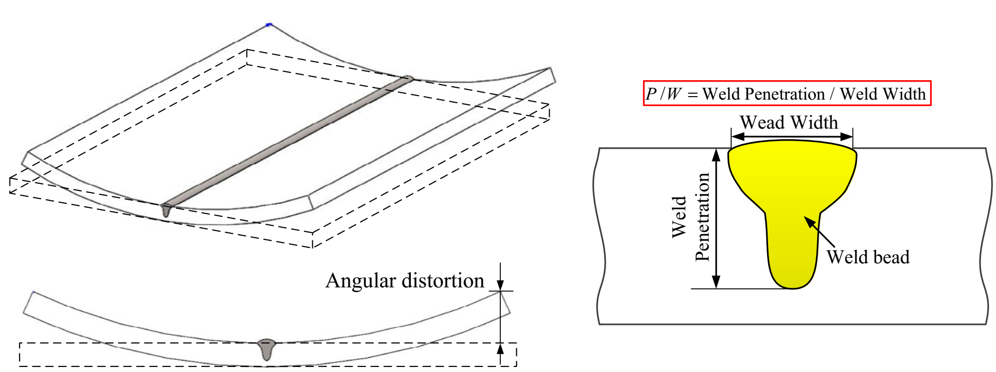

Fig. 2. The illustration of angular distortion and P/W.