On-line monitoring of penetration state in laser-arc hybrid welding based on keyhole and arc features

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Abstract. Incomplete penetration is a typical defect in laser-arc hybrid welding. On-line monitoring of welding process is an important method to assess welding quality. In laser-arc hybrid welding, there is a strong correlation between keyhole, arc and incomplete penetration. Therefore, an on-line monitoring method of penetration state based on keyhole and arc features is proposed in this paper. In the proposed method, the images of keyhole and arc in laser-arc hybrid welding are captured by high-speed camera, and then the keyhole and arc features are extracted by image processing algorithm. Finally, the features are used as input to classify the penetration state using SVM model. The results show that the SVM model based on keyhole and arc features can accurately identify the penetration state.

1. Introduction

Laser-arc hybrid welding technology is an efficient and new welding method. It can give full play to the advantages of two kinds of welding heat sources, which enhances the bridging ability of groove gap and obtain greater welding penetration. It has been gradually applied successfully in automobile manufacturing, oil pipeline, shipbuilding and other industries [1-4]. In laser-arc hybrid welding, the weld formation is more sensitive to the selection of process parameters. And in industrial production, it is difficult to ensure that the process parameters can be adjusted very accurately, for example, too high laser power may lead to root humping, and too low power will produce incomplete penetration [5]. Penetration state is one of the most important indexes to assess the welding quality in laser-arc hybrid welding, and the on-line identification of penetration state is an important method to realize the quality control. Wang et al. [6] used two high-speed cameras to capture the welding images of laser-arc hybrid welding, and reconstructed the penetration state of the weld bottom through signal processing algorithm. Bunaziv et al. [7] studied the penetration efficiency of laser-arc hybrid welding of thick plate. Ghosal et al. [8] used artificial neural network to monitor the penetration of laser-arc hybrid welding of magnesium alloy, and the prediction result is very accurate. It has been pointed out in the references [6, 7, 9] that keyhole and arc are related to penetration state, but there is no research on using keyhole and arc features to predict penetration state at the same time.

This paper proposes an on-line monitoring method of laser arc hybrid welding penetration state based on keyhole and arc features. Firstly, a 4 kW fiber laser and a digital welding machine are used for the laser-arc hybrid butt welding of 2205 duplex stainless steel. Then, the images of the keyhole and arc in the welding process are captured by a high-speed camera. The features of keyhole and arc are extracted by image processing. Finally, the features are used as the input and the penetration states as the output, and the SVM model is used to identify and classify the penetration states.
2. Experimental setup
The laser-arc hybrid welding system used in this experiment is shown in Figure 1. The fiber laser IPG YLR-4000 is used in this experiment. The maximum power is 4 kW and the laser wavelength is 1070 nm. Using FRONIUS TPS4000 digital welding machine, the maximum welding current is 400 A. The robot is ABB IRB4400 industrial robot. In order to prevent the welding head from being damaged due to laser reflection, the incident laser is deviated from the vertical axis by 8 degrees. The arc welding equipment set-up is displayed in Figure 1 and the arc torch angle is 60 degrees. The material is 2205 duplex stainless steel. The angle of groove is 20 degrees and the seam gap is 0. Before welding, the surface of the workpiece is polished to remove the oxide film and cleaned with acetone. The images of keyhole and arc in the welding process are captured by using paraxial high-speed camera (Phantom V611) and auxiliary light. In order to obtain clear images of keyhole, arc and molten pool, an 808 nm near infrared narrow band filter is installed on the high-speed camera to remove the interference of metal vapor and laser. The frame rate of the high-speed camera is set to 5000 frames per second. We use the mixed gas (80% Ar + 20% CO₂) as the shielding gas with flow rate of 25 L min⁻¹ to be consistent with the industrial standard.

![Figure 1. Schematic diagram of butt welding experiment.](image)

3. Image processing and feature extraction
According to the section 1, it is known that the keyhole and arc are related to penetration state. When the penetration state changes, the size and direction of various forces in the keyhole will change accordingly, resulting in the change of the shape of the keyhole. And compared with the incomplete penetration state, in the penetration state, the keyhole penetrates from the bottom of the weld, reducing the reflection of light from the keyhole wall, so the attenuation of light radiation will appear, which is reflected in the visual image. In short, the keyhole area in the penetration state is smaller than that in the incomplete penetration state. On the other hand, the size of arc also affects the penetration state. When the arc volume changes, the laser absorption of the arc will change, which will affect the laser penetration ability of the material, and eventually lead to the change of penetration. Therefore, we extract the features of keyhole and arc to analyze the penetration state. Figure 2 shows the specific process of keyhole and arc feature extraction. The first step is to capture the keyhole and arc from the original images, remove a lot of useless information, reduce the impact of spatter and other noise around, so as to make the information...
of keyhole and arc more accurate. Then, the image enhancement algorithm is used to enhance the contrast between the keyhole and arc and the surrounding environment. Secondly, median filtering algorithm is used to eliminate noise interference such as outliers and line segments. The threshold segmentation operation converts the filtered image into a binary image, so that the keyhole and arc are composed of white pixels, surrounded by black pixels. Finally, by calculating the number of white pixels, the shape data of keyhole and arc are obtained.

Figure 2. The keyhole and arc features extraction processing, (a) the original image, (b) segmentation, (c) grayscale processing, (d) median filtering, (e) binarization, (f) edge extraction.

Figure 3 shows the different penetration states of the weld bottom. Figure 4 shows three feature curves extracted from 6000 images in two kinds of penetration states, which are the area of keyhole, the perimeter of keyhole and the area of arc. 3000 on the left are the features of penetration state and 3000 on the right are the features of incomplete penetration state. By comparing the features of the two penetration states, it can be found that the average values of the area and perimeter of the keyhole are different in two penetration states, and the average value of the area of the keyhole in the penetration state is smaller, which also verifies the previous conclusion. Through the signal processing algorithm, the high frequency component of the feature in Figure 4 is removed and then smoothed. The result of processing is shown in Figure 5. It can be seen that the difference between the features in penetration state and incomplete penetration is more obvious.

Figure 3. Penetration status of weld bottom.
4. Modeling of weld penetration states identification

SVM model is an implementation method of statistical learning theory [10, 11]. This method has strong learning ability for small samples and good generalization performance [12]. The basic idea is to find a hyperplane to divide the samples into two categories and make the interval between them maximum. The optimal hyperplane is applied to linearly separable data in feature space, and its basic idea is shown in Figure 6. The solid points and hollow points in the graph are sample sets, and the classification interval is $2/||w||$, where $2/||w||$ is the Euclidean norm of $w$. The classification plane satisfying this condition is the optimal classification line, and the sample points on the line $W^T X + b = 1$ and the line $W^T X + b = -1$ are the support vectors. The problem can be formulated as:
In this paper, SVM model is used to classify the penetration state of laser-arc hybrid welding. The features of the keyhole area, the keyhole perimeter, the Y-coordinate of the keyhole centroid and the arc area are selected as the input in the SVM model, while the output are the penetration states at the bottom of the weld. The classification label is 0 for the penetration state and 1 for the incomplete penetration state. The 6000 samples mentioned above are used as the training set, and another 600 samples are selected as the test set. In order to speed up the convergence speed of the model and improve the accuracy of the model, all samples in the training set and the test set are normalized to the interval \([-1,1]\).

In the SVM model, the radial basis function (RBF) is used as kernel function. The RBF kernel is one of the most widely applied kernel functions, usually in its Gaussian form [13]:

\[
k(x, x') = \exp\left(-\frac{||x - x'||^2}{2\sigma^2}\right)
\]

Then, the optimal penalty parameter \(c\) and kernel function \(\gamma\) are obtained by cross validation at each grid point through grid search method. The optimized parameters are substituted into the SVM model for training, and the final classification model is obtained. Using this model to predict other test samples, the test accuracy is 98.17%, and the results are shown in Figure 7.

![Figure 6. Typical binary classification problem.](image)

![Figure 7. Classification results of test set.](image)
5. Conclusions
In this paper, based on the keyhole and arc features, a SVM model is established to on-line monitor the penetration state of laser-arc hybrid welding. Some conclusions can be drawn as follows:

(1) By analyzing the signals, it can be found that the features are different in the two penetration states, which verifies the correlation between keyhole, arc and penetration state.

(2) The SVM model based on the keyhole and arc features can be used to predict the penetration state, and the prediction accuracy is as high as 98.17%, which lays the foundation for on-line monitoring of penetration state in laser-arc hybrid welding.

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