High-power disc laser welding quality detection based on photoelectric sensing system

Weiwei Huang¹,², Deyong You², Yanxi Zhang³, Xiangdong Gao*⁴

¹Guangdong Provincial Welding Engineering Technology Research Center, Guangdong University of Technology, Guangzhou, China
²Guangdong Provincial Welding Engineering Technology Research Center, Guangdong University of Technology, Guangzhou, China
³Guangdong Provincial Welding Engineering Technology Research Center, Guangdong University of Technology, Guangzhou, China
⁴Guangdong Provincial Welding Engineering Technology Research Center, Guangdong University of Technology, Guangzhou, China

¹1755767937@qq.com
*Corresponding author: gaoxd@gdut.edu.cn

Abstract. In order to monitor the quality of laser welding in real time, a photoelectric sensor system is designed, which can collect the light radiation signals of the welding area in real time. The signals are converted into voltage signals by the photoelectric sensor and collected by the data acquisition card. Matlab software is used to analyze the power spectrum of the collected data. It is found that visible light and reflected light have similar power spectrum characteristics through experimental analysis, and the number of peaks and peak frequencies of the power spectrum have an obvious relationship with the quality of the weld. The results show that the detection system can effectively monitor welding defects in real time.

1. Introduction
This Laser welding is applied to various fields of products manufacturing industry because of its characteristics such as narrow heat-affected zone, concentrated heat power, high welding speed and high-quality shaping [1-2]. Especially high-power laser welding has been widely applied in industries such as car manufacturing, aerospace manufacturing, and shipbuilding [3-5]. Automatic processing puts forward higher requirements for rapid identification of welding defects. Therefore, real-time control of welding defects is of great significance for improving production efficiency and ensuring welding quality.

The optical radiation signal mainly comes from laser beam and welding area, molten pool, splashes and plasma all emit strong optical radiation. Optical visual monitoring methods are currently widely used [6-7]. Through this method, a large amount of reliable data can be obtained, such as molten pool, splash and metal vapor and other morphological characteristics. In terms of welding detection, a lot of research work has been done on laser welding online monitoring at home and abroad and effective results have been achieved. You Deyong [8-9] designed an experience-driven recognition system that combines photoelectric sensors, visible light vision sensors and auxiliary light vision sensors to detect strength steel welding. It is found that there is a local linear relationship between the thermal radiation...
intensity in the coaxial direction and the collapse of the surface keyhole during the welding process. This method can effectively judge the quality of the welding. And the experience-driven identification system can replace the high-cost, complex-structured sensor monitoring system. Colombo [10] developed a new simple detection device for fiber laser welding process, which called "Through Optical Combiner Monitoring". The device can be easily installed on the fiber laser and the detection effect of the device can be comparable to traditional monitoring. Zhang Yanxi [11] extracted the photoelectric signals, visual features, and spectral features of the welding process through multi-optical sensors, and established a deep belief network model based on these features to realize online monitoring of laser welding status. Jiang Wuzhi [12] used a double-layer photoelectric sensor system to collect the optical radiation signals of the metal vapor and molten pool, and analyzed the frequency spectrum characteristics when the weld was defective, which can effectively detect the quality of laser welding.

The sensor system designed in this paper uses two photoelectric sensors to collect the visible light signal and the reflected light signal during the high-power laser welding process. The optical signals are converted into voltage signals and amplified by a voltage amplifier, and then voltage signals were collected by the data acquisition card. The power spectrum characteristics of the weld under different process parameters are analyzed, and the power spectrums are used to characterize the welding quality.

2. EXPERIMENTAL SETUP
The experiment was carried out on a platform equipped with a high-power disc laser welding device Trumpf-16002, and the actuator was a MOTOMAN six-axis robot. Fig.1(a) depicts the experimental setup of this research. The wavelength of the disc laser is 1030nm, the diameter of the laser beam is 300μm, the laser power range is 2kw~16kw, the focus position range is -4mm~4mm, the welding speed range is 2m/min~4m/min, and the shielding gas is argon. The welding material in this research is 304 stainless steel. The dimensions of the workpiece are 150 mm in length, 10 mm in width, and 50 mm in thickness. The data acquisition system is mainly composed of photoelectric sensor module.

Specifically, the scanning laser head collects the light radiation from the welding area through a one-way mirror and a focusing lens, and transmits it to the photoelectric sensor module. In order to capture the intensity signal of visible light and reflected light, a beam splitter is pre-installed in the laser head. The light signal from the welding area is transmitted to the visible light photodiode (wavelength 380-780nm) and reflected light photodiode (wavelength 1030nm) through the spectroscope in the photodiode box, and finally received by the oscilloscope after being amplified. The sampling frequency of the photodiode is 500k Hz. The higher the sampling frequency of the photoelectric sensor, the faster the response speed. Therefore, using photoelectric sensors has good real-time performance.

![Figure 1](image-url)
Fig. 1(b) shows the detection principle of the welding process. In the laser welding process, when a high intensity laser beam acts on molten metal, strong evaporation occurs on the surface[13]. Once the pressure caused by the strong evaporation exceeds the hydrostatic pressure and the surface tension of the melt, the melt can be pushed away to produce a keyhole. Meanwhile, the evaporated metal gas is ejected from the keyhole, which is known as a laser-induced “vapor plume”. The radiation of plume is captured as visible light signal by visible photoelectric sensor. A part of the laser returns to the original path after multiple reflections from the molten pool, and is captured by the reflected light photoelectric sensor as a reflected light signal.

| Experiment No. | Power (kW) | Speed (m/min) | Defocus (mm) | Gas (L/min) |
|---------------|-----------|---------------|--------------|-------------|
| 1             | 6         | 3             | -3           | 30          |
| 2             | 7         | 3             | -3           | 30          |
| 3             | 8         | 3             | -3           | 30          |
| 4             | 9         | 3             | -3           | 30          |
| 5             | 10        | 3             | -3           | 30          |
| 6             | 11        | 3             | -3           | 30          |
| 7             | 12        | 3             | -3           | 30          |
| 8             | 13        | 3             | -3           | 30          |
| 9             | 14        | 3             | -3           | 30          |

The welding experiment parameters are tabulated in Table 1. The laser power was changed while the welding speed, defocus and protective gas flow were kept unchanged. The data of 9 groups of optical radiation signals in the laser welding process were collected. By changing the laser power, the weld seams appear in a stable state and a defect state respectively.

### 3. RESULTS AND DISCUSSION

#### 3.1. Stable Status

When the process parameters are changed, the weld appears stable status and defect status. The welds with experimental numbers 1, 2, 8 and 9 were selected for analysis, and their corresponding images of welds and power spectral density were shown in Fig. 2 and Fig.3.

![Figure 2](image1.png)

*Figure 2* Weld seam and power spectral density.  (a)Laser power is 6kw; (b)Laser power is 7kW
Fig. 2(a) shows the image of weld seam and power spectral density (PSD) curve when the laser power is 6kW. The number marked in the figure represents the abscissa of the peak position, that is, the frequency of the peak position. Firstly, the PSD curves of visible light and reflected light are compared. The PSD value of visible light is generally larger than the PSD value of reflected light. The reason is shown in Fig. 1 (b). As the first reaction zone between the laser beam and the metal, the molten pool absorbs most of the energy of the laser beam. Then laser is reflected several times in the inner wall of the molten pool, and only a small part of the laser returns to the original path and is captured by the reflected light sensor. The metal vapor evaporates from the liquid metal in the molten pool by heating. Most of the metal vapor is in visible light band, and a small amount is in near-infrared band, so most of the optical radiation generated by metal vapor is captured by visible light sensor. Therefore, the signal intensity of visible light is greater than the signal intensity of reflected light, which means that the power of visible light is greater than the power of reflected light. Converted to the power spectral density curve, the power of visible light per unit frequency is also greater than that of reflected light.

When the power is 6kW, the PSD curve of visible light has 12 peaks, and the PSD curve of reflected light has 10 peaks. The waveforms of the PSD curves of visible light and reflected light are generally very similar. There is still a slight difference. When the frequency is 99609Hz and 199951Hz, the PSD curve of visible light has a peak; on the contrary, the PSD curve of reflected light has a wave trough. As shown in the green curve in Fig. 2(a), when the frequencies are approximately 94970Hz, 104492Hz, 195312Hz and 204589Hz, the PSD curve of reflected light appears a wave peak, but at this time, the PSD curve of visible light is close to a wave trough. It is worth noting that the weld seam has a very good surface quality.

In order to prove that when the weld surface quality is good, the PSD curve of the photoelectric signal has the law described above, then the PSD curve of the photoelectric signal with the power of 7kW and the surface quality is good is analyzed. Fig. 2(b) shows the image of weld seam and PSD curve when the laser power is 7kW. It can be seen from Fig. 2(a) and Fig. 2(b) that when the weld seam has a good surface quality, the PSD curve of the photoelectric signal has a very high degree of similarity. The frequencies of the peaks at the corresponding positions in the two figures are mostly the same, and only a few of the peaks marked in red have an error of 200Hz-500Hz. Under the background of the high frequency sampling rate of 500k Hz, this is a reasonable error range.

In order to prove that when the weld surface quality is good, the PSD curve of the photoelectric signal has the law described above, then the PSD curve of the photoelectric signal with the power of 7kW and the surface quality is good is analyzed. Fig. 2(b) shows the image of weld seam and PSD curve when the laser power is 7kW. It can be seen from Fig. 2(a) and Fig. 2(b) that when the weld seam has a good surface quality, the PSD curve of the photoelectric signal has a very high degree of similarity. The frequencies of the peaks at the corresponding positions in the two figures are mostly the same, and only a few of the peaks marked in red have an error of 200Hz-500Hz. Under the background of the high frequency sampling rate of 500k Hz, this is a reasonable error range.

3.2. Defect Status

Fig. 3(a) shows the weld image and PSD curve when the laser power is 13kW. In this case, there are obvious humping defects in the weld seam. Compared with the stable status, the PSD curves of visible light and reflected light in the defect status are not significantly different from those in the low frequency
region from 0 to 2000 Hz. But in the high frequency region from 2000 Hz to 250 kHz, the PSD curves of the photoelectric signal have undergone great changes. The number of peaks in the PSD curve of visible light is reduced to 7, and the number of peaks in the PSD curve of reflected light is reduced to 8. In particular, in the PSD curve of visible light, the peaks with frequencies of 34912 Hz, 64697 Hz, 135010 Hz, 164795 Hz, and 235107 Hz disappeared. As for the PSD curve of the reflected light, the two peaks on the left and right of 0.5 kHz almost disappear. The two peaks on the left and the right with frequencies of 1 kHz, 1.5 kHz, and 2 kHz are constantly approaching so that there is a tendency to form one peak. In addition, the peak of 235107 Hz on the PSD curve of reflected light disappeared and replaced by the peak of 243652 Hz, which is getting closer and closer to 250 kHz.

Similarly, for the purpose of verifying the similarity of PSD curves of photoelectric signals in defect status, the weld data processed with the laser power of 14 kW was selected for analysis, as shown in Fig. 3 (b). Observing the image of the weld seam, more defects including humping and dent appeared on the surface of the weld. The PSD curves of the photoelectric signals are very similar to that in the case of 13 kW. Furthermore, compared with the case where the laser power is 13 kW, the two peaks on the left and right with frequencies of 1 kHz, 1.5 kHz, and 2 kHz are closer, and the frequency of the last peak is also closer to 2.5 kHz. It is proved that the PSD curves of the photoelectric signals are consistent in the defect status.

According to the above analysis, it can be known that when the weld is in a smooth or defective status, the PSD curves of the photoelectric signal have different characteristics, which can provide a basis for identifying welding defects.

4. CONCLUSIONS

In this paper, a disc laser welding photoelectric sensor system is designed to capture the visible light signal and the reflected light signal from the welding area simultaneously. Optical signals are converted into voltage signals by the photoelectric sensor, and finally collected by the acquisition card. Through the PSD analysis of the collected data, the welding statuses and welding defects in the welding process can be judged. The following conclusions can be reached.

1. When the surface of the weld is smooth, the peak number of PSD curve of the photoelectric signal is more than 10.
2. When defects such as humping or dent appear in the weld, the peak number of PSD curve of photoelectric signal is reduced to less than 10.
3. It is proved that PSD curve of the photoelectric signals is consistent when the welding seam is in the same status through comparative experiments.

Acknowledgment

This work was partly supported by the National Natural Science Foundation of China (51805090) and the Guangzhou Municipal Special Fund Project for Scientific and Technological Innovation and Development (202002020068).

References

[1] T. Y. Liu, J. S. Bao, J. L. Wang and J. Gu, “Laser welding penetration state recognition method fused with timing information”, Chin. J. Lasers, in press. J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.
[2] Z. Q. Chen, X. D. Gao, Y. Wang and D. Y. You, “Weldment back of weld width prediction based on neural network during high-power laser welding”, Trans. China Weld. Inst., 2018, vol. 39, pp. 48–52.
[3] P. S. Wei, K. C. Chuang, J. S. Ku and T. DebRoy, “Mechanisms of spiking and humping in keyhole welding”, IEEE Trans. Compon. Packag. Manuf. Technol., 2012, vol. 2, pp. 383-394.
[4] M. M. Atabaki, N. Yazdian, J. Ma and R. Kovacevic, “High power laser welding of Thick steel plates in a horizontal butt joint configuration”, Opt. Laser Technol., 2016, vol. 83, pp. 1-12.
[5] Y. Zhang, F. Z. Li, Z. C. Liang, Y. Y. Ying, Q. D. Lin and H. Y. Wei. “Correlation analysis of penetration based on keyhole and plasma plume in laser welding”, J. Mater. Process. Technol., 2018, vol. 256, pp. 1-12.

[6] X. F. Liu, C. B. Jia, C. S. Wu, G. K. Zhang and J.Q. Gao. “Measurement of the keyhole entrance and topside weld pool geometries in keyhole plasma arc welding with dual CCD cameras”, J. Mater. Process. Technol., 2017, vol. 248, pp. 39-48.

[7] H. Roozbahani, P. Marttinen and A. Salminen, “Real-time monitoring of laser scribing process of CIGS solar panels utilizing high speed camera”, IEEE Photonic. Tech. L., 2018, vol. 30, pp. 1741-1744.

[8] D. Y. You, “Hybrid driven based online detection of high power laser welding process”, Guangzhou: Guangdong University of Technology, 2014, pp. 84-101.

[9] D. Y. You, X. D. Gao and S. Katayama, “WPD-PCA-based laser welding process monitoring and defects diagnosis by using FNN and SVM”, IEEE Trans. Ind. Electron., 2015, vol. 62, pp. 628-636.

[10] D. Colombo and B. Previtali, “Through Optical Combiner Monitoring of Fiber Laser Processes”, Int. J. Mater. Form., 2010, vol. 3, pp. 1123-1126.

[11] Y. X. Zhang, D. Y. You; X. D. Gao and S. Katayama, “Online Monitoring of Welding Status Based on a DBN Model During Laser Welding”, Engineering, 2019, vol. 5, pp. 169-185.

[12] W. Z. Jiang, C. X. Liang, H. C. Wu and G. T. He, “YAG laser welding quality detection based on double-layer photoelectric sensing system”, Sensor World, 2017, vol. 23, pp. 13-19

[13] Y Huang, C Shen, X R Ji, F Li, Y L Zhang and X M Hua. “Correlation between gas-dynamic behaviour of a vapour plume and oscillation of keyhole size during laser welding of 5083 Al-alloy”, Journal of Materials Processing Technology, 2020, vol 283, pp 116721.