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Laser welding monitoring with multisensory data fusion: A brief review

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Abstract As digital manufacturing is being implemented across industries, the automation of the laser welding process is a crucial step to enhance production efficiency. To monitor the in-situ welding process, there are several approaches to detect the electromagnetic and mechanical waves on various frequencies for comprehending laser beam-material interaction. Five sensing techniques, namely the optical microphone, welding camera, inline coherent imaging, infrared camera, and heat flux sensor, can be employed to identify distinct features in the laser welding process. These features include pore formation, melt pool geometry, weld bead topography, keyhole depth, and thermal distribution. The discussion of a proposed welding system designed with compatibility for multisensory data fusion is included, both on its capabilities and potential challenges, to offer guidance of welding monitoring.

Keywords: Laser welding monitoring, inline coherent imaging, surface topography, keyhole depth, welding camera, acoustic emission

1 Introduction

Laser welding is a versatile joining method with high precision and flexibility applied in various industries, and the operational scope spans from a few millimeters in thickness to several meters in length. The high-power density contributes to a high production rate, compared to arc welding and plasma welding [1]. As the laser welding process involves highly complex physical mechanisms like laser absorption, conductive and convective heat transfer and hydrodynamic melt pool flow, it takes substantial research effort to understand these phenomena and to enhance the stability and repeatability [2]. Consistent quality is crucial for ensuring structural safety, so reduction of defects is the main goal. This review paper explains how a laser welding is conducted and how to improve the quality with the monitoring data from various types of sensors. A welding system is proposed to outline a structured hierarchy of data and information and to demonstrate how these elements can improve the current system.

2 Mechanism

The common types of lasers used for welding are fiber laser, disk laser, and carbon dioxide laser with the wavelength of near-infrared or far-infrared spectrum, depending on its laser media. Coherent stimulated emission has a fixed frequency as monochromatic radiation, excluding the presence of ionizing radiation.

2.1 Laser beam-metal interaction

To understand the laser welding process, light-matter interaction, or to be specific, laser beam-metal interaction is discussed here in the microscopic manner. When the laser beam reaches the material surface, the radiation provides the energy to heat up the metals into liquid state and vapor state, then the thermal energy which conducts to the heat-affected zone (HAZ) to change the mechanical properties on the base metal. Depending on energy input and interaction time, lasers can do ablation, welding and cutting [3] [4]. If the penetration depth exceeds the thickness of the base metal, the melt pool falls from the spot, which is called drop-through or piercing [5]. For in-situ observation of the laser welding process, the X-ray phase contrast method can be used for identifying keyhole and melt pool [6] [7]. The dynamic radiography, or the X-ray imaging with high frame rate, can reach 50 thousand frames per second, meaning the increment change in 0.02 millisecond can be analyzed [8]. The classical problem of laser-induced cavitation bubble dynamics can be investigated attributed to the highly resolved images [9] [10] [11]. Note that these experiments with X-ray phase contrast imaging are conducted e.g., in synchrotrons, the large-scale facilities for high brightness and fast acquisition time. From the in-situ observation of laser welding, the keyhole, consisting of gaseous metal, can be seen at the laser beam-metal interaction point, and its geometry should be analyzed to ensure the full penetration without bubbles trapped during the keyhole wall closing stage [12] [13]. In some research papers, the keyhole is called vapor capillary, and its geometry is discussed in the manner of shape, size, and depth [14]. Since the keyhole behaves as an efficient point to absorb the laser energy, the relation of absorption rate between laser energy and welding speed is investigated with water-calorimetric method or integrated sphere radiometry [15] [16] [17]. Ideally the metals joining method aims to form the metallic bonds on the interface; however, in less favorable instances, it results in some defects like pores, undercuts, cracks, deformation and oxidation to a certain context [18] [19]. Due to the unstable keyhole movement, high thermal gradient, and insufficient melt flow, the laser welding speed has an upper process limit which prevents it from faster production [20] [21] [22] [23]. Therefore, it is important to monitor the keyhole, melt pool and weld bead to ensure the weld quality. Meanwhile, the mechanical properties of the weld joints must be suitable to avoid e.g., the fatigue crack initiation [24] [25]. The monitoring results can be incorporated to correlations of crack initiation location and fatigue strength.

2.2 Sensor development

Over the last few decades, sensor technology has made significant advancement in terms of accuracy, speed and versatility thanks to the miniaturization of integrated circuits and improvement in optic systems. The enhanced signal processing techniques with the novel algorithms and the development of materials in sensors with better sensitivity also contribute to the sensor development. In addition, the high computing power enables the real-time monitoring and control system with visualization and user interface to evaluate the quality and make informed decisions. The system with these sensors can extract meaningful information and identify patterns or anomalies, which are beneficial for developing a smart system to enhance the weld quality. These sensors include low-coherence interferometry, infrared cameras, high-speed welding cameras with active illumination, pyrometers, photodiodes, acoustic emission sensors, and heat flux sensors, which will generate data to be interpreted and integrated to understand the weld quality. Before the processed data can be combined to evaluate the weld, the data alignment is needed to ensure the time frame is compatible with each other and synchronized to have a common starting point and finishing line.

3 The trend in laser welding technology

This review paper briefly categorizes the welding techniques into three stages, depending on the involvement of machines on implementation and perception, meanwhile the ability for the algorithm to improve the data interpretation quality based on the experience is also discussed here as it is the trend of developing the smart welding system. Below is the table to show the three stages of the welding system.

Table 1. The three stage of welding system based on the perception and implementation.

Welding system	Human perception	Machine perception
Human implementation	1 Conventional welding training	Not in discussion
Machine implementation	2 Predefined welding automation	3 Future adaptive system

3.1 Conventional welding training

When welding is performed by human workers, the training includes the types of welding symbols and materials properties. While doing the hand-held laser welding, there is pictorial drawing well defined by the mechanical design for the welders to follow. Thus, hand-eye coordination is important, but there is limited endurance and recognition capability. Restricted by nature, the visible light spectrum spans from 380 nm to 760 nm and the welding helmet or welding goggles filter out the radiation beyond the visible light, which may result in a loss of detailed information about weld quality [26].

3.2 Predefined welding automation

As the automation gains prevalence on the production line, the welding equipment installed on the robotic arm can enhance the production rate. The trajectory of the weld line is determined by predefined welding parameter values and is executed using the robotic arm, so the quality is more consistent and uniform than the preceding stage. Real-time monitoring equipment can be installed to measure the quality, but the adjustment is not made in time. Typically, laser welding is carried out in this category. Post-weld X-ray inspection is run to examine the pores and cracks after solidification of the melt pool. Though this process can verify the quality, the delay of the defects formation and discovery is prolonged, and there is no integrated feature for perturbation cancellation in the system. To spot the anomalies on time and to mitigate the defects, the future adaptive system is needed [27].

3.3 Future adaptive system

To develop an adaptive system, both advanced sensing and control technologies are used for adjusting the laser welding parameters during the welding process. There are several types of real-time feedback that can be used to analyze the welding process, and the first one is the seam trajectory. The seam tracking capability relies on the ahead sensing line and control architecture to adjust the position and orientation for a curved line or a straight line [28]. If the robotic arm is installed on a mobile platform, the working area of the seam tracking welding can be extended [29]. Next, the second type of the feedback is the melt pool geometry, and it can exhibit the thermal condition on the surface. When excessive energy from the laser causes a larger melt pool, it is prone to drop-through. Therefore, either the laser power should be reduced or the welding speed should be increased before the piercing takes place. The real-time feedback from these non-destructive testing can reduce the delay between defect formation and defect discovery, and it can be applied in other types of welding like hybrid laser welding too. After discussing the feedback, there is one trend that many researchers start to investigate, which is the deep learning algorithm to correlate the signature of defects and predict the crack initiation [30] [31]. Thus, the application of these features will be considered to develop the adaptive system for better weld quality control.

4 Proposed welding system

Based on the trace of signal from the laser welding process, there are three types of inspection to be discussed in this system, which are ultrasound wave signal, electromagnetic wave signal, and heat flux on the surface. The corresponding sensors tailored to each signal type are involved in collecting data, subsequently interpreting it into observable phenomena. For example, a welding camera can capture visible light to provide insights of melt pool geometry and surface topology. Similarly, a thermal camera can detect the infrared light to show the thermal distribution across the surface. These phenomena are beneficial for researchers to comprehend the properties after a considerable number of samples are tested.

With the identified properties over time, the domain knowledge can be cultivated to inform future decision on welding parameters. As deep learning algorithm has increasing prevalence in the manufacturing industry, it becomes imperative to assess its rule in the overall process too. If the human learning represented by the blue box in Figure 1 is replaced by machine learning, the system cannot function because the algorithms for computational statistics lack the capability to understand the properties or to establish the domain knowledge that includes the relevant theories, principles and relationships within the domain. Therefore, in this review paper, only the connection between sensing level and features level, marked with purple arrows, would incorporate the algorithms to interpret the certain phenomena from the welding process. Noteworthy that some phenomena utilize multiple sensors in parallel, which is planned as the engineering redundancy for enhancing system robustness. One sensing technique that has yet to receive substantial attention in the community is the heat flux monitoring during welding, and this aspect is integrated in the proposed system discussed in this review paper.

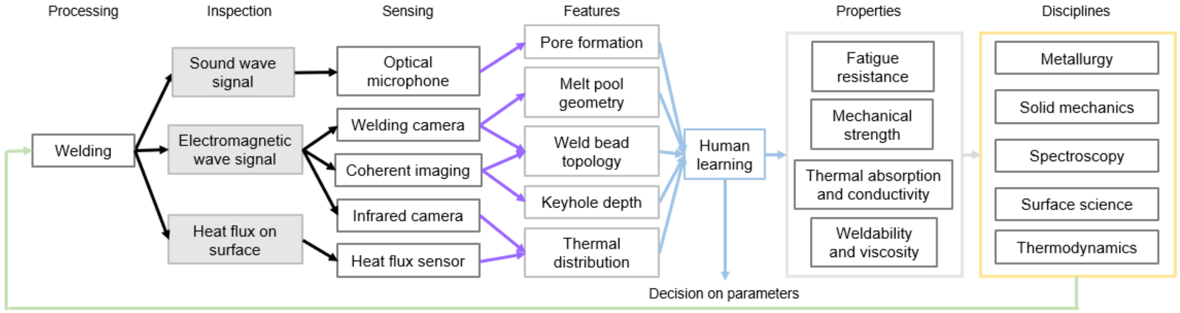

Figure 1. The proposed welding system showing the level of data and information.

4.1 Ultrasonic signal processing

During the welding process, the formation of spatters and pores emits distinctive acoustic signals detectable by a microphone [32]. As acoustic emission is essentially a mechanical wave propagating through the air, both mechanical microphone and optical microphone can be used for monitoring. However, these two types of microphones operate on the different mechanisms to generate the data. In this proposed system, the optical microphone is preferred as it has high sensitivity and significantly broader frequency response.

Since the laser sensor detects the air density change during the welding process, there is no mechanical moving part in the microphone. The reason that it can cover a wider frequency range from 2 kHz to 2 MHz is that the signal is processed through Fourier transform to convert the time-domain signal to frequency-domain signal. In this way, the frequency range is not constrained by membranes as in conventional mechanical microphones. Subsequently, the acoustic emission signals can be analyzed by filtering and correlation, or convolutional neural network, which is a machine learning algorithm designed for pattern recognition [33].

4.2 Multispectral image processing

Regarding electromagnetic waves, or optical signals, there are four aspects to be discussed, firstly, low-coherence interferometry; secondly, active pulsed laser illumination; thirdly, the structured light; and fourthly, radiative emission from the surface based on its temperature.

First part, optical coherence tomography, utilizing low-coherence interferometry, enables the real-time measurement of keyhole depth, and the imaging technique can generate point cloud representing the targeted surface area [34]. The path length is derived from the time difference of the sample point and the reference point. With a high sampling rate reaching several hundreds of kilohertz, its interested area includes not only keyhole depth, but also the seam profile and weld bead profile.

Second part, rapid pulsed laser illumination enables high-speed photography with the welding camera [35]. As the narrow band-pass filter can concentrate the detection of the monochromatic laser light source, the process radiation would hardly cause overexposure in the images. The acquisition rate of the high-quality welding images can easily reach thousands of frames per second, given the short exposure time that can capture illumination from the brief laser pulse, preferably on the microsecond scale.

Third part, structured light can present the surface profile when it traverses along the welding direction. The calculation of the surface profile involves knowledge of the angle and position between the bar pattern and the sensor. Noteworthy that the technique of photogrammetry can be used to construct the weld profile and to measure the misalignment without the structured light, but they are conducted as the post-weld inspection, rather than in-situ monitoring [36] [37]. Hence, if photogrammetry can be integrated to the welding camera without relying on structured light, it would be a notable achievement as it overcomes challenges associated with varying radiation from the melt pool.

Fourth part, the electromagnetic radiation emitted from the surface of the base metal and heat-affected zone can reveal the surface temperature. As laser energy is absorbed in the keyhole and extends to the surrounding area, the thermal gradient can be measured with the infrared thermal camera [38]. Other than the infrared thermal camera, photodiodes can be used to measure the surface temperature, but the drawback is that it only shows the overall emission rather than the thermal gradient [39]. It is important to note that all four parts rely on electromagnetic signals, and the potential overlapping of wavelengths may lead to interference among these different sources. In case the situation worsens, the spatial and temporal relations need to be taken into consideration to avoid constructive or destructive interference.

4.3 Heat flux monitoring

During the laser welding process, the plume and fume are the undesirable byproducts, containing metal particulates and metal oxides, that can impede optical sensors from receiving signals. Therefore, heat flux sensors would be valuable to measure the heat flow without potential interference from the fume or plume. These heat flux sensors should be mounted on the surface of the base metal for the thermal conduction from the keyhole and heat-affected zone, so there will be multiple sensors on the both sides of the workpiece to form an array to calculate the changing temperature [40] [41]. Once the temperature at the contact points is determined, it can be used to analyze the thermal phenomena and phase transformation in the solid state with the numerical model according to the metallurgical composition [42].

4.4 Multisensory data fusion

After each sensor receives the signal, it will be routed to the processing module for feature extraction, and the classification algorithms are used to evaluate the weld quality based on the significance of these features [43]. The algorithms for feature extraction may use conventional statistical filtering model or convolutional neural networks model, and the defects such as pores, undercuts and cracks are identified when specific features are derived from the deployed sensors. To establish an efficient monitoring system, the detection rates from various sensor combinations will be compared for a comprehensive evaluation of performance. This iterative process can optimize the monitoring system for enhanced weld quality assessment.

5 Potential problems

Challenges ahead, there are some common problems existing in previous experiments and will persist in the future experiments, such as the plume formation, shielding gas, and the beam shift [44] [45]. The solution of the plume formation may be incorporating the inert gas like argon to prevent oxidation, but it also decreases the keyhole stability, which may lead to increased pores formation. Moreover, as the plume is present within the atmospheric environment, the particulates can actually cause the laser beam shift [2] [46]. This type of associated dilemma needs more comprehensive approaches to solve in the future research. Additionally, from the computational perspective, the substantial volume of data from high-speed cameras and other high frame rate sensors demands considerable computing power, so achieving real-time result is a challenge to the algorithms on both sensors and computers in the adaptive welding system.

6 Conclusion

Digitalization in the manufacturing industries will increase the prevalence, and it can contribute to a safer workspace and more efficient production. This review paper presents the current research on the welding monitoring techniques and proposes an adaptive welding system with the brief introduction of each type of sensing method. Positioned as a foundation for future welding system development, more experiments are scheduled to validate the proposed system structure and to affirm the increased stability and repeatability. The research team is committed to achieving a more autonomous manufacturing system as a key objective.

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8 CRediT authorship contribution statement

Li-Wei Hsu: Methodology, Formal analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. Antti Salminen: Conceptualization, Writing – review & editing, Supervision, Resources, Funding acquisition

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