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Probing the impact of process variables in laser-welded aluminum alloys: A machine learning study

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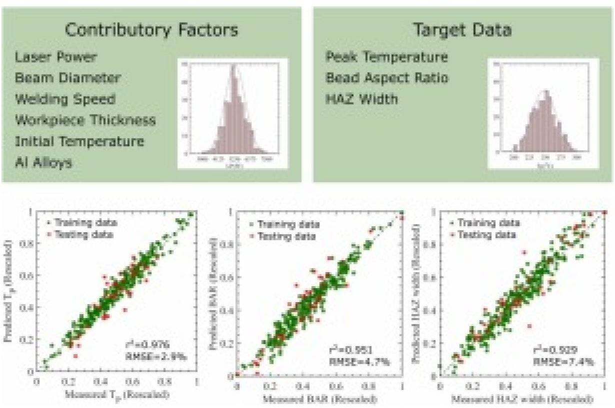
Abstract

This paper presents a pioneering approach, Bayesian machine learning (ML), for the estimation and characterization of critical laser welding features in Aluminum alloys, encompassing peak temperature, heat-affected zone width, and bead aspect ratio. The methodology involved constructing a laser welding database utilizing finite element simulations (FEM). The distinctive advantage of the Bayesian ML model lies in its capability to address challenges associated with excessive approximation and to account for uncertainties in parameters. This results in precise and resilient predictions of laser weld parameters across a spectrum of aluminum alloys. The findings underscored the model's efficacy in forecasting output targets, although regression analysis unveiled unique characteristics in data distribution and outliers specific to aluminum alloys. These outliers were primarily linked with the melting range of aluminum alloys, leading to the Al7075 alloy having the lowest prediction, and the Al1100 alloy the highest within the ML model.

Additionally, the normalized average weight functions of input parameters were illustrated, clarifying their differing importance concerning diverse types of Al alloys in precisely forecasting output objectives. In light of these explanations, it remains consistent that laser power (LP) and welding speed (WS) inputs hold substantial sway across all alloys, while workpiece thickness (WT), beam diameter (BD), and initial temperature (IT) played comparatively lesser roles. Ultimately, this work contributes to a more profound comprehension of the relationships between input features and the geometrical and thermal behavior of laser-welded Al joints.

Graphical Abstract



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Introduction

Laser welding has emerged as a critical joining technique in the manufacturing industry, revolutionizing the way various materials are bonded together [1], [2]. Among the multitude of applications, laser welding plays a significant role in the fabrication of aluminum alloys, owing to their widespread use in industries such as automotive, aerospace, and construction [3], [4]. The unique properties of aluminum alloys, such as lightweight, high strength-to-weight ratio, and excellent corrosion resistance, make them a preferred choice for numerous structural components [5], [6], [7]. Laser welding offers several advantages for aluminum alloys, including precise control of process parameters and the ability to achieve high-quality welds with minimal distortion [8]. One of the key benefits of laser welding for aluminum alloys is the fine-tuning of process parameters. The laser's focused heat source allows for precise control over the energy input, resulting in localized melting and minimal heat-affected zones (HAZ) [9], [10]. This controlled heating enables the joining of thin sections and dissimilar aluminum alloys with varying melting points, ensuring superior weld quality and mechanical properties.

Laser welding for aluminum alloys offers numerous advantages but faces challenges such as high reflectivity and thermal conductivity. Overcoming these obstacles requires careful parameter selection to achieve optimal weld quality and minimize defects. For this purpose, several works have been carried out to study the relation between process parameters and weld quality, specifically concerning weld geometry, thermal characteristics and defects generation, in the laser welding [11], [12], [13], [14]. To give some examples, Beiranvand et al. [15] investigated the impact of magnesium (Mg) evaporation on laser welding of aluminum alloys, suggesting that Mg vapor in the plasma plume affected laser absorption, weld profile, and penetration. in another study, Ai et al. [16] developed a 3D numerical model is to analyze the behavior of the molten pool in oscillating laser welding of aluminum alloys, specifically focusing on the "∞" shaped oscillating process for 5052 aluminum alloy. By employing oscillation, the maximum temperature and flow velocity are reduced, resulting in a more stable and shallower molten pool. By combining numerical simulations and experimental observations, Liu et al. [17] discovered that the implementation of beam oscillation resulted in the stabilization of fluid flow within the weld pool, leading to a reduction in porosity and an enhancement in keyhole stability. Xu et al. [18] found that the electromagnetic frequency and laser power significantly influenced sagging height and back surface roughness, while magnetic induction intensity had a smaller impact in welding of A5083 aluminum alloy. Geng et al. [19] presented a numerical model to evaluate the heat transfer, and solidification behavior in full-penetration laser welding of thin 5083 aluminum sheets. The model successfully predicted weld dimensions, demonstrating the dominant role of heat conduction in heat transfer. Wen et al. [20] studied the impact of keyhole instability on weld penetration in laser welding of thin-sheet Al alloy. Their findings contributed to a theoretical understanding of keyhole formation and offered insights for achieving desired weld penetration and improving weld quality in pulsed laser welding processes.

In recent years, the application of machine learning (ML) techniques in the prediction of laser welding processes has gained significant importance, particularly in the analysis of weld geometry and heat generation within the welds [21], [22], [23], [24]. Several works have explored this field, shedding light on the advancements made in this area. For instance, Cao et al. [25] focused on monitoring the penetration state during laser welding by fusing multi-sensing signals using cross-attention-based techniques. This approach allows for real-time monitoring and control of the welding process. Deep learning algorithms were also utilized to predict the penetration depth in Al/Cu laser welding [26]. By incorporating information from spectrometer signals and CCD images, the model achieves high accuracy in predicting the weld quality and penetration depth. Tsai et al. [27] proposed a systematic approach for determining optimal laser power and scanning speed in lap joint laser welding of stainless steels. Highly accurate simulations and artificial neural network models were used to screen processing maps and select parameters that minimize porosity, heat affected zone size, and residual stress.

In this work, we address the characterization of process parameters for laser welding in aluminum alloys by leveraging the power of a Bayesian ML model. By incorporating Bayesian techniques, we are able to account for the inherent uncertainty in the data, enabling more reliable predictions and informed decision-making. To collect the necessary data, we employed a finite element method (FEM) simulation approach, specifically focusing on studying the effects of welding speed and laser power on heat affected zone width, aspect ratio of weld bead width to depth, and peak temperatures for samples of varying thicknesses. This FEM-based data collection process provides a comprehensive understanding of the parametric effects, allowing to optimize the laser welding process for different thicknesses of aluminum alloys.

Section snippets

FEM simulation

In the initial phase of ML model implementation, the collection of extensive and dependable data is crucial for the training process. To achieve this, we conducted FEM simulations of laser welding across a broad spectrum of process parameters, encompassing various types of aluminum alloys. The current study applied a three-dimensional conical Gaussian heat source model specifically chosen for its proficiency in accurately representing the keyhole shape formation observed in high-density laser…

ML methodology

ML evaluation frameworks have attracted significant attention in the study of welding process performance. Scholars have been exploring the impact of varying parameters on this process, as documented in references [30], [31]. This evaluation methodology has played a pivotal role in enabling the creation of a data-driven model to characterize the features and behavior of welded alloys. As these models rely on data, a larger dataset could enhance the precision of characterization. Conventional…

Results and discussion

By employing regression analysis, it is possible to assess the model's accuracy and reliability by comparing the predicted values against the actual values. This enables a comprehensive evaluation of the regression model's effectiveness in capturing the underlying relationships and making precise predictions. In Fig. 4**a**, the parity plots depict a comparison between the measured and predicted values of output targets. The developed Bayesian ML model exhibits strong performance in predicting Peak …

Conclusions

In conclusion, this study has introduced an innovative Bayesian machine learning (BML) approach as a breakthrough method for accurately estimating and characterizing crucial laser welding parameters in Aluminum alloys, including heat-affected zone width, peak temperature, and bead aspect ratio. The main outcomes are as follow:

1. The Bayesian ML model's outstanding capability to tackle challenges related to approximation and parameter uncertainties has been a highlight of this research.…

2. The…

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CRediT authorship contribution statement

In this collaborative effort, **Faouzi Didi** led the conceptualization and design of the project, while **Harikumar Pallathadka** focused on data collection and Bayesian machine learning model development. **Sherzod Abdullaev** provided crucial insights into Bayesian machine learning techniques, while **Renas Rajab Asaad** conducted numerical simulations and data generation. **Shavan Aska** contributed to data analysis and practical implications, and **Noor Hanoon Haroon** contextualized the research within the...

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper....

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