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Heat flux measurement, a tool for laser beam welding process monitoring – preliminary study

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Abstract. Accurate measurement of reflected heat flux in laser welding is critical for process monitoring but remains challenging due to the limitations of traditional techniques. This study introduces transverse heat flux sensors (THFS) based on the Seebeck effect in bismuth single crystals, enabling real-time measurements with nanosecond response times. Experiments were conducted at 1.5 kW (conduction), 5.5 kW (transition), and 9.5 kW (keyhole) power settings. Results showed distinct heat flux differences: 1.25 kW/m² with ± 0.25 kW/m² fluctuations in conduction mode, decreasing to 500 W/m² with ± 80 W/m² fluctuations in keyhole mode. Two THFS – one fixed above the focal point and one movable – were used to explore spatial heat flux distribution. This study demonstrates the feasibility of THFS for laser welding monitoring, paving the way for advanced process control through numerical simulations and machine learning.

1. Introduction

Laser beam welding has become a cornerstone of modern manufacturing due to its ability to achieve high-precision joining of metals with minimal heat-affected zones (HAZ) [1 and many other]. It is widely used in industry for its controlled heating, narrow weld bead, and the ability to weld a wide range of metals, including dissimilar materials such as carbon steel and stainless steel. However, ensuring consistent weld quality remains challenging, particularly when welding dissimilar metals. Issues such as the formation of brittle phases in the weld, martensitic transformation in the heat-affected zone, and solidification cracking in the fusion zone can significantly degrade the strength and quality of the welded joint. Additionally, precise monitoring of the thermal dynamics involved in the process is crucial. Current techniques for process monitoring include thermal imaging, vision systems, acoustic emission, and optical signal analysis. While these methods provide valuable insights into features such as weld pool dimensions, keyhole stability, and other process characteristics, they often suffer from limitations such as low temporal resolution, susceptibility to environmental noise, and an inability to directly measure heat flux.

To address these challenges, this study introduces a novel approach using transverse heat flux sensors (THFS) based on the Seebeck effect in bismuth single crystals [2, 3]. These sensors offer several advantages over traditional methods, including faster data sampling rates (on the order of tens of nanoseconds), simpler equipment and analysis requirements, and the ability to

determine the spatial directionality of heat flux. This preliminary study investigates the feasibility of THFS for monitoring heat flux during laser welding processes, focusing mainly on three distinct welding modes: conduction (1.5 kW), transition (5.5 kW), and keyhole (9.5 kW).

Furthermore, the validation of computational fluid dynamics (CFD) and finite element method (FEM) models is critical for accurately simulating the thermal and metallurgical behavior during laser welding [4]. In the future, the integration of artificial intelligence (AI) and machine learning (ML) models, leveraging heat flux data, could enable real-time monitoring and control of the welding process, enhancing both efficiency and quality.

2. Methods

2.1 Experimental setup

The experiments were conducted between January and March 2025 at the Laser welding cell in Quad Tech Turku, Laboratory of Mechanical Engineering in University of Turku [5]. A fiber laser (IPG YLR-10000) with a wavelength of 1070 ± 5 nm was used for the tests. The welding process was performed on steel specimens measuring $400 \times 50 \times 12$ mm³ using an IPG Photonics WL HIT head equipped with a 150-mm collimator, a focal length of 400 mm, and a working distance of 348 mm to the steel samples.

Two transverse heat flux sensors (THFS) were employed in the experimental setup. These sensors are based on the transverse Seebeck effect in bismuth single crystals and generate a voltage proportional to the heat flux, enabling real-time measurements with a response time of tens of nanoseconds. The THFS sensors were positioned as follows:

Sensor 1 : A 6.2×5 mm² heat flux sensor with a sensitivity of 9 mV/W was mounted directly above the laser's focal point on the body of the welding head. This sensor measured the vertically upward-reflected heat flux.

Sensor 2 : A 10×10 mm² heat flux sensor with a sensitivity of 10 mV/W was mounted on a movable arm. This allowed the sensor to be repositioned at various hemispherical angles around the focal point while maintaining a constant distance of 19 cm from the laser focus. The angular positions tested included azimuthal angles of 60°, 120°, and 180°, as well as polar angles of 30°, 60°, and 90°.

Data from both sensors were recorded using a Hioki data logger (model LR8431).

The general arrangements during the experiments are shown on the Figure 1.

2.2 Testing Procedure

The laser welding process was conducted mainly under three power settings: 1.5, 5.5, and 9.5 kW. For each power level, the laser beam was automatically moved by an ABB robotic manipulator over a distance of 50 mm according to a pre-programmed path. After completing the weld at one power level, the power was adjusted, and the process was repeated. Three tests were performed on each steel plate, resulting in three welds per plate to ensure statistical significance.

Data were collected and analyzed to determine the magnitude and variability of heat flux in each mode. Specifically, the vertical-axis heat flux differences among the conduction, transition, and keyhole modes were evaluated. Additionally, the second sensor's data will be analyzed further to map the heat flux distribution in the hemisphere surrounding the laser focus, providing insights into the three-dimensional energy distribution during different welding modes.

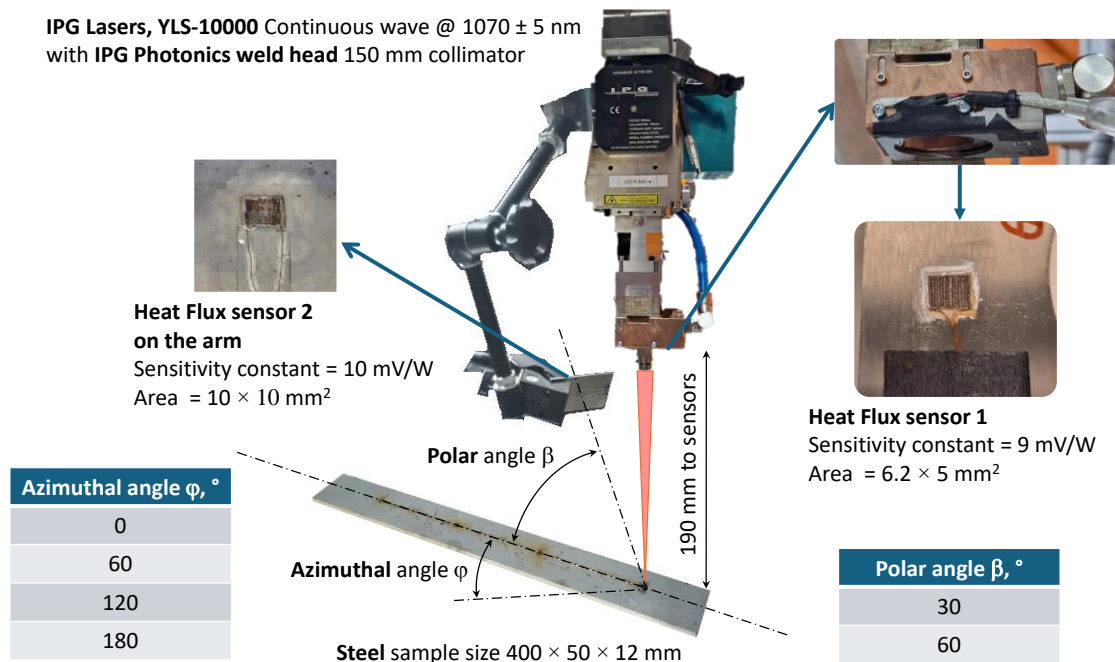


Figure 1. THSF installations and coordinate system during the experiments

3. Results

The raw sensor signal - without conversion to heat flux density, for three laser power mentioned above - is presented in Figure 2 (a-c) . As shown, the amplitude of the sensor signal and its fluctuations decreased with increasing laser power. This trend objectively indicates a reduction in reflected radiation, which can be attributed to the transition from conduction mode to keyhole mode welding.

In all cases, the time origin ($t = 0$ s) corresponds to the moment the laser was turned on. The observed trends align with the expected physical behavior of the interaction between the laser

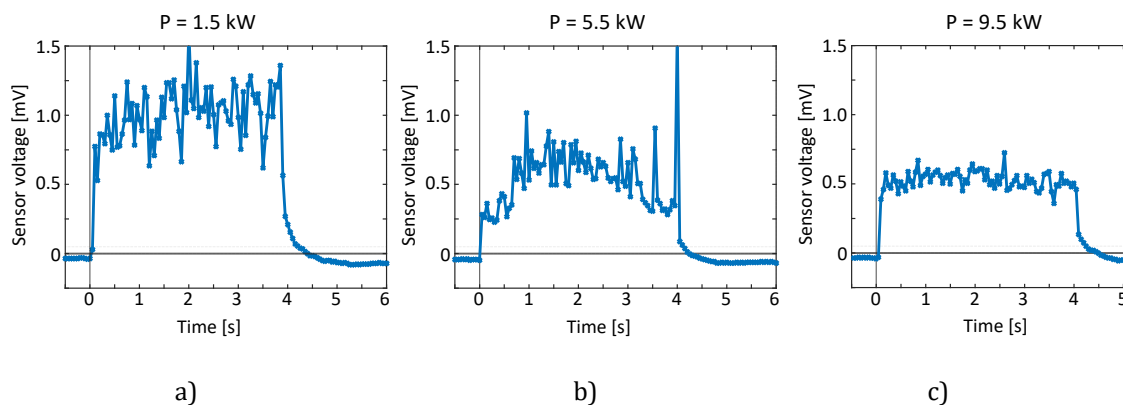


Figure 2. Sensor voltage at different modes

beam and the workpiece, where higher power leads to deeper penetration and changes in the reflection characteristics of the material surface.

The experimental results revealed distinct differences in heat flux across the three welding modes.

3.1 Heat Flux Measurements for Each Mode

Conduction Mode (1.5 kW): The heat flux measured by the sensor reached an average value of approximately 1.25 kW/m^2 , with fluctuations of around $\pm 0.25 \text{ kW/m}^2$. This high heat flux is characteristic of the conduction mode, where energy absorption is primarily dominated by conductive heat transfer mechanisms.

Transition Mode (5.5 kW): In this mode, the average heat flux decreased to approximately 600 W/m^2 , with reduced fluctuations of about $\pm 200 \text{ W/m}^2$. The transition mode represents an intermediate state between conduction and keyhole welding, showing a balance between conductive and radiative heat transfer processes.

Keyhole Mode (9.5 kW): At the highest power setting, the heat flux further decreased to approximately 500 W/m^2 , with minimal fluctuations of around $\pm 80 \text{ W/m}^2$. This reduction in heat flux is attributed to the formation of a stable keyhole during welding, which alters the energy distribution and reflection characteristics of the material.

3.2 Statistical Analysis of Heat Flux

A detailed statistical analysis of the heat flux data highlights the following trends:

In the conduction mode (1.5 kW), the heat flux was approximately twice as high as that observed in the keyhole mode (9.5 kW).

The standard deviation of heat flux in the conduction mode was more than three times higher compared to the keyhole mode, indicating greater variability in heat flux under low-power conditions.

The transition mode (5.5 kW) exhibited slightly higher heat flux values than the keyhole mode but showed a standard deviation similar to that of the conduction mode, reflecting its intermediate nature between the two extremes.

3.3 Insights into Heat Flux Distribution

These findings underscore the complex relationship between laser power, welding mode, and heat flux distribution. Notably, the decrease in heat flux with increasing laser power can be attributed to changes in the interaction between the laser beam and the material, such as the formation of a vapor capillary (keyhole) at higher powers, which modifies the energy absorption and reflection characteristics.

Further analysis of the data collected from the second sensor, positioned on the movable arm, will enable the creation of a heat flux map in the hemisphere surrounding the laser focus. This mapping will provide valuable insights into the three-dimensional energy distribution during different welding modes, contributing to a deeper understanding of the thermal dynamics involved in laser welding processes.

After processing and averaging the heat flux measurement data for each welding mode, the local time-averaged heat flux density distributions were plotted in polar coordinates. Since the

sensor was positioned in steps of 30° in elevation and 60° in azimuth during the experiments, the processed data are presented in the form of piecewise linear curves (Figure 3).

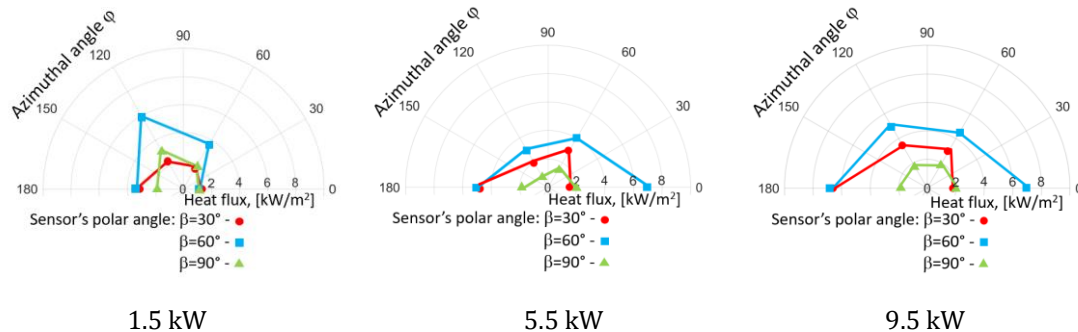


Figure 3. Time-averaged heat flux for different welding mode

The time-averaged heat flux values in the vertical direction (corresponding to a polar angle of 90°) are shown in the figure 4 as a function of laser power, summarizing the results from all conducted experiments. Figure 4 presents also compiled data from earlier experiments conducted at various laser power levels: 1, 2, 4, 4.5, 5, 6, 7, 8, 9, and 10 kW. A general trend of

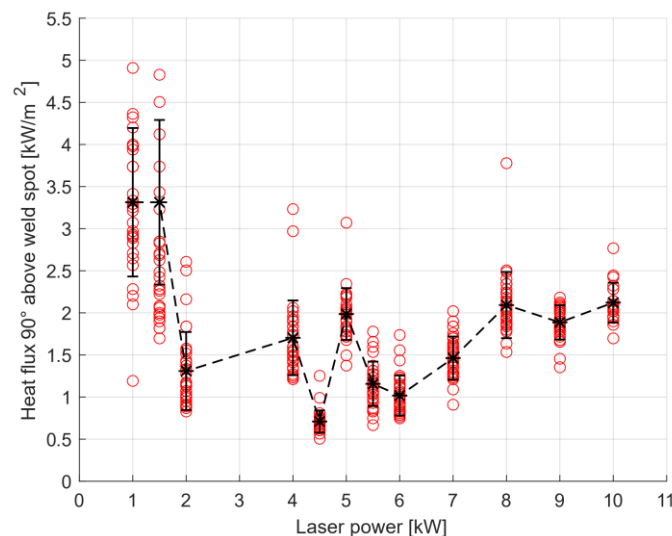


Figure 4. The time-averaged heat flux values in the vertical direction

increasing reflected power is observed starting from approximately 2 kW, indicating a shift in the interaction dynamics between the laser beam and the material surface. Notably, significant fluctuations in the reflected power are evident within the 4...6 kW range, which corresponds to the transition mode. These fluctuations likely reflect the inherent instability and dynamic nature of the laser-material interaction during the transition between conduction and keyhole welding modes.

4. Discussion

This study introduces the transverse heat flux sensor (THFS) as a valuable tool for high-resolution thermal monitoring in laser welding applications. The unique capability of THFS to measure the direction and magnitude of heat flux with microsecond-level time resolution positions it as a promising alternative to conventional techniques like thermal imaging, which typically suffer from slower response times and require complex calibration procedures.

The experimental observations show clear trends in heat flux behavior across the three distinct welding regimes – conduction, transition, and keyhole – which correspond well to their underlying thermal mechanisms. In conduction mode, the heat flux exhibited high peaks and greater variability, indicative of strong localized conduction without significant vaporization. The transition mode presented intermediate behavior, suggesting the onset of more dynamic energy redistribution. In contrast, the keyhole mode, dominated by vaporization, led to more uniform heat flux patterns with lower peak values, likely due to the more distributed nature of energy absorption.

These results not only confirm the sensor's sensitivity to rapid thermal changes but also highlight its potential to contribute to real-time diagnostics of process stability and mode identification. Future work should explore the integration of multiple THFS units to map the spatiotemporal evolution of heat flux and validate the data against numerical simulations for predictive process modeling.

5. Conclusion

This preliminary investigation confirms the suitability of transverse heat flux sensors (THFS), based on the Seebeck effect in bismuth single crystals, for monitoring laser welding processes with high temporal fidelity. THFS offers several advantages over conventional measurement techniques, including rapid data acquisition, streamlined analysis, and the capability to resolve directional heat flow.

Distinct heat flux profiles were recorded for conduction (1.5 kW), transition (5.5 kW), and keyhole (9.5 kW) welding modes. Notably, heat flux decreased with increasing laser power, reflecting changes in energy absorption and distribution mechanisms. These insights underscore the relevance of THFS as a diagnostic tool for distinguishing between different welding regimes.

This work, conducted without external funding, exemplifies a low-cost and innovative approach to enhancing understanding and control of laser-based manufacturing processes. Looking forward, further studies will analyze data from a second sensor to develop spatial heat flux maps. In combination with computational models and machine learning, THFS could enable next-generation smart control systems for laser welding and other high-energy manufacturing technologies.

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