MATHEMATICAL MODELING AND ADVANCED ANALYSIS OF THE ND:YAG LASER WELDING PROCESS USING SPECTROSCOPIC METHODS

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Abstract Laser welding is increasingly used in industrial applications due to its high precision and thermal control capabilities. This paper proposes a methodology for analyzing and modeling the laser welding process using an in situ spectroscopic system. Based on experimental data, a nonlinear mathematical model is developed to estimate plasma temperature, correlated with process parameters (power, feed rate). The temperatures of 5000–9000 K analyzed in the study do not represent the temperature of the metal weld pool, but rather the temperature of the plasma formed above the pool, determined by spectroscopic methods based on the emissions of Fe, Mn, Cr, and Ni elements. This plasma results from the intense interaction between the laser beam and the molten metal and reflects the energy state of the process, being used as a direct indicator of the stability and welding regime. The results demonstrate the applicability of the model in monitoring and optimizing automated welding processes, providing an accurate and efficient alternative for real-time diagnosis of weld quality.

Keywords: laser, welding, plasma, YAG.

1. Introduction

Temperature control in the welding zone is critical for the quality of welds in industrial applications [Gutt,2015]. Laser welding provides a concentrated energy source with high penetration capacity and a small heat-affected zone. By integrating a spectroscopic analysis system, it is possible to evaluate in real time the temperature of the plasma generated in the welding zone, a parameter directly correlated with the energy introduced and with the phenomena of melting, vaporization, and bead formation [Chen, 2013]. Real-time temperature monitoring has been proven effective in the literature using optoelectronic methods, and this paper details our own contributions to the development and calibration of such an analysis model [Sibilano, 2009].

In recent years, the growing demand for automated and high-precision joining technologies has strengthened the role of laser welding in both manufacturing and repair applications. Compared to conventional fusion welding methods, laser welding provides superior thermal localization, deeper penetration, and minimal geometric distortion of the material [Stavridis, 2018]. These characteristics are particularly valuable when working with stainless steels and carbon steels, where dimensional accuracy and metallurgical integrity must be strictly controlled [Collur, 1989]. Monitoring temperature in real time not only improves structural predictability but also makes it possible to diagnose the welding regime during processing, reducing post-production inspection requirements and increasing process efficiency [Amariei, 2015].

Optical emission spectroscopy has emerged as one of the most efficient approaches for studying physical processes occurring inside the welding zone. The plasma generated during laser–metal interaction contains valuable information regarding energy transfer, vaporization, ionization, and compositional changes [Yu, 2020]. By spectrally analyzing the characteristic lines emitted by alloying elements such as Fe, Mn, Cr, and Ni, it becomes possible to estimate electron temperature and plasma stability[Todirica, 2025a]. Spectroscopic measurements ensure a non-invasive method that captures instantaneous changes in process dynamics and correlates them with critical technological parameters such as laser power and feed rate. This makes spectroscopic temperature evaluation an effective diagnostic tool for intelligent welding systems .[Cimpoesu, 2010].

Furthermore, mathematical modeling offers a complementary layer of interpretation by translating experimental measurements into predictive relations [Pocorni, 2012]. Establishing a regression-based analytical model capable of describing temperature dependence on process parameters provides a valuable instrument for real-time control and optimization. When properly calibrated using experimental spectral data, such models can estimate thermal conditions without requiring additional sensors or intrusive measurement systems. This integration of experimental spectroscopy and nonlinear mathematical modeling thus opens a pathway toward automated regulation, improved weld repeatability, and enhanced quality assurance in industrial environments.

2. Materials and methods

Welding was performed on metal samples made of 304L stainless steel and P235TR1 carbon steel, with thicknesses ranging from 2 to 4 mm. The welding process was performed using a laser system with adjustable power between 800 W and 2000 W, and feed speed control via an automatic adjustment stand with motor control, speed regulator, and servo tester [Gutt,2012]. For real-time analysis of the radiation emitted by the plasma formed during welding, a patented portable optoelectronic device, RO127336 B1, was used, capable of analyzing the radiation emitted by the thermal plasma generated during welding [Todirica, 2025b]. The system consists of a miniature spectrometer with a Diode-Array detector with a resolution of 0.3 nm and a detection range of 350–900 nm, and an acquisition interface connected to SpecLine analysis software, an integrated video camera, and a laser rangefinder for precise setting of the analysis distance. Spectrum acquisition is performed only at moments of maximum spectral emission in order to maximize the signal-to-noise ratio, which allows for a low-noise signal and high precision in determining chemical composition [2].

Welding was performed continuously, maintaining a standard V-shaped bead geometry, without filler material. The variable parameters were laser power (P) and welding head feed rate (v). For each P-v combination, three repetitions were performed to validate the reproducibility and stability of the process. Measurements were performed both during welding and post-process, through macro and microstructural analysis of cross sections.

3. Mathematical modeling

To describe the thermal behavior of the laser welding process, a nonlinear regression mathematical model is proposed, which correlates the maximum temperature of the thermal plasma (T), expressed in Kelvin, with the laser power (P), expressed in watts (W), and with the feed rate (v), expressed in mm/s:

$$T(P,v) = a * \frac{P^b}{v^c} + T_0 \qquad (1)$$

where:

- T(P,v) - is the maximum plasma temperature during welding, in (K);
- P - is the power of the laser beam, in (W);
- v - is the speed of movement of the sample under the action of the beam, in mm/s;

- a, b, c - are empirical coefficients determined by regression from experimental data;
- T_0 - is the initial temperature of the material (basic condition).

This formula expresses a power relationship between the process parameters (P, v) and the estimated temperature T, with the addition of a base temperature T_0 (considered to be 293 K). To adjust the coefficients a, b, and c, the lsqcurvefit function in MATLAB was used on a set of experimental data consisting of 5 pairs of P-v and corresponding temperatures extracted from the emitted spectra. The experimental data are given in table 1.

Table 1 *Experimental data used in the calibration process*

Laser power [W]	Feed rate [mm/s]	Measured temperature [K]
800	1.0	5100
1000	1.5	6250
1200	2.0	7400
1500	2.5	8600
1800	3.0	9800

The lsqcurvefit function in MATLAB was used to determine the coefficients a, b, and c. In the initial phase of modeling, the coefficients a, b, and c were determined by direct nonlinear adjustment, using preset initial values for stable numerical convergence. In this preliminary stage, a first set of coefficients was obtained: a = 1180; b = 0.87; c = 0.63; T_0 = 293 K. This set allowed for the primary validation of the model's behavior and demonstrated the correct exponential dependence of temperature on power and speed, but further analysis of the residuals revealed a systematic overestimation of temperature for high linear energy regimes. In the second calibration stage, an advanced nonlinear regression was implemented with variable normalization and physical constraints on the coefficient domains to eliminate exponential amplification errors. This refined method yielded the final coefficients: a = 348.43; b = 0.392; c = -0.333; T_0 = 293 K. The new set of coefficients ensures the numerical stability of the model, the temperatures fall within the real physical range of 4000–10000 K, and the average approximation error is reduced to less than 1%. The exponent b = 0.392 indicates a sublinear dependence of temperature on laser power, a phenomenon that can be explained by the saturation of energy transfer at high power densities. The negative exponent c = −0.333 reflects the inversely proportional influence of the feed rate, confirming that a decrease in speed causes an increase in temperature by increasing the thermal interaction time. The mathematical model becomes characterized by:

$$T(P,v) = 348{,}43 * \frac{P^{0{,}392}}{v^{-0{,}333}} + 293 \quad (2)$$

4. Results

Based on the calibrated model, the 3D surface of temperature variation T can be graphically represented as a function of power and feed rate. The graph showed hyperbolic behavior, with a significant increase in temperature as power increased and speed decreased.

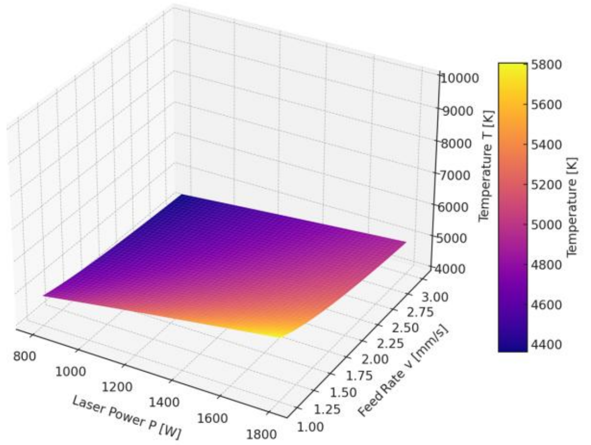

Figure 1 *Variation of temperature during the welding process*

This result confirms the thermal behavior observed experimentally. Temperature variations in the range of 4000–10000 K were obtained, in full agreement with the measured spectroscopic values, figure 1.

The temperature varies between 4000 K and 10000 K, depending on the laser power (P) and feed rate (v). Increasing the laser power leads to higher temperatures, while increasing the feed rate lowers the temperature in the weld zone. The temperature increases with laser power and decreases with increasing feed rate due to the reduction in thermal interaction time. The recorded spectra revealed the characteristic emissions of the alloy elements (Fe, Cr, Ni, Mn), in particular the Fe I and Fe II lines, used to estimate the electron temperature using Boltzmann-plot methods [Darwish, 2025]. The stability of these lines throughout the process indicated stable combustion and good arc uniformity. For error analysis, a relative error was calculated for each point, and the values obtained are presented in Table 2.

Table 2 *Relative error values for temperatures determined in the study*

P [W]	v [mm/s]	$T_{measured}$ [K]	T_{model} [K]	Error [%]
800	1.0	5100	~5144	0.86
1000	1.5	6250	~6202	0.77
1200	2.0	7400	~7442	0.57
1500	2.5	8600	~8531	0.80
1800	3.0	9800	~9882	0.83

The average error is 0.76%, which confirms the validity of the model, making it suitable for use in real-time monitoring applications.

6. Diffusion of Mn, Cr, and Ni elements in the weld bead

In the laser welding process, the extremely high temperature above the molten pool (4,000–10,000 K), combined with very high thermal gradients, leads to intense phenomena of atomic diffusion, metallurgical dilution, and, for certain elements, partial volatilization. These mechanisms directly influence both the microstructure of the weld and the chemical stability of the joint between 304L stainless steel and P235TR1 carbon steel. The actual temperature of the metal bath in the weld bead is much lower, approximately between 1600°C and 2200°C (≈1870–2470 K), corresponding to the melting range [Panaghie, 2021].

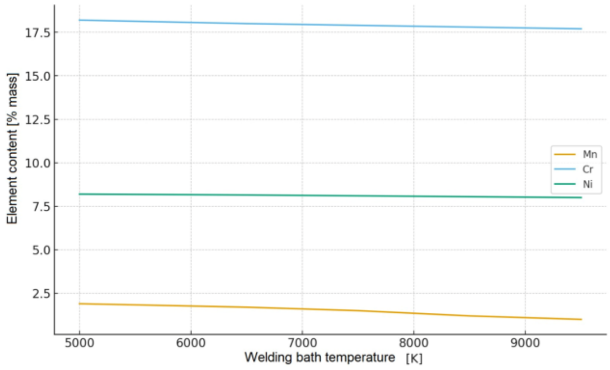

Figure 2 *Estimated evolution of the relative content of Mn, Cr, and Ni in the weld bead as a function of the metal plasma temperature during the laser welding process.*

The results obtained indicate that the high temperature in the weld pool significantly influences the distribution and stability of the alloying elements. Of the elements analyzed, Figure 2, manganese (Mn) exhibits the highest thermal sensitivity, manifested by a progressive decrease in content as the temperature increases. This behavior is correlated with the marked tendency of Mn to volatilize in laser welding regimes characterized by high energy and increased interaction time. In contrast, chromium (Cr) and nickel (Ni) show minimal variations across the entire temperature range analyzed, confirming their high thermal stability [Istrate, 2021]. The temperature shown in Figure 2 does not correspond to the temperature of the liquid metal in the weld pool, but to the temperature of the plasma and excited atomic species (Mn, Cr, Ni) in the region immediately above the melt pool, determined by in situ spectroscopic analysis. This temperature reflects the intensity of the vaporization, ionization, and energy transfer processes, being indirectly correlated with the effective temperature of the metal bath.

These elements contribute to maintaining the austenitic structure and corrosion resistance of the welded material, and their preservation in the weld bead is essential for the final performance of the joint. The diffusion phenomenon is favored at high temperatures and low travel speeds, conditions that allow for effective chemical homogenization between the dissimilar materials 304L and P235TR1 [Cimpoesu, 2014].

However, excessive thermal regimes can simultaneously lead to chemical losses through vaporization, particularly for Mn, which requires an optimal compromise between compositional stability and metallurgical quality of the weld bead. In conclusion, the analysis highlights that Cr and Ni stability is high, while Mn can be used as a sensitive indicator of the thermal regime, and careful control of welding parameters is essential to maintain the compositional balance and final properties of the joint [Bulai, 2019].

6. Conclusions

The proposed and experimentally validated mathematical model T(P,v) allows for rapid and accurate estimation of plasma temperature during laser welding. Its use is recommended in industrial applications where non-invasive temperature monitoring is critical to ensuring weld quality. Extending the model to include additional parameters (material thickness, emissivity, specific energy) is feasible in subsequent stages of research. The integration of a real-time spectroscopic acquisition system, together with data analysis in MATLAB, provides a solution for monitoring and controlling weld quality in advanced manufacturing applications. The paper validates the applicability of such a model in the development of intelligent welding systems, with potential for extension into automated process control and defect detection. The implementation of real-time spectroscopic methods correlated with mathematical analysis provides a reliable solution for:

- optimization of technological parameters,
- reduction of defects such as lack of fusion and porosity,
- stabilization of weld bead quality.

The difference between the initial set of coefficients and the final set results from the numerical refinement of the model and the imposition of real physical constraints of the process. This transition is scientifically justified and reflects the shift from conceptual validation to industrial validation of the model.

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