A Parameter–Thickness Relationship Model for Air-Assisted Mild Steel Cutting Using a 1 kW Fibre Laser- An AI assisted Empirical and Computational Study

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Abstract: This study establishes robust empirical parameter–thickness relationship models essential for optimizing air-assisted mild steel cutting using a 1 kW fiber laser system. Efficient industrial application requires precise knowledge of how cutting parameters—particularly speed and focus position—must be adjusted to accommodate increasing material thickness while maintaining process stability and quality. The empirical phase involved determining the maximum cutting speed and corresponding optimal focus position for mild steel thicknesses ranging from 0.3 mm to 4.0 mm, all while maintaining a constant laser power of 100% (1 kW) and an assist gas pressure of 15 bar. Regression analysis by Artificial Intelligence revealed that the cutting speed exhibits an Exponential Decay relationship with thickness.

Keywords: *Fibre Laser Cutting, Regression, Artificial Intelligence, Optimization, Thickness Relationship.*

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I. INTRODUCTION

Laser cutting stands as a cornerstone technology in modern advanced manufacturing, favored for its high precision, rapid processing speeds, minimal thermal distortion, and versatility across a broad spectrum of materials [5]. The evolution of laser sources, particularly the advent of high-power fiber lasers, has revolutionized material processing by offering superior efficiency, beam quality, and reliability compared to traditional CO_2 systems [6, 2].

The quality and efficiency of the laser cutting process are critically dependent on the precise interplay of numerous operational parameters, including laser power, cutting speed, focus position, gas pressure, and nozzle geometry [4]. For industrial applications, the most vital and challenging task is determining the optimal set of parameters that maximize the cutting speed while ensuring adequate quality for a given material thickness. This dependency is highly non-linear, making trial-and-error procedures time-consuming and costly [3].

This study focuses on the air-assisted cutting of mild steel, a ubiquitous material in structural and automotive industries. While air assist offers a cost-effective and readily available alternative to pure inert gases (like nitrogen) or reactive gases (like oxygen), the process complexity increases due to the multi-component nature of the assist gas, influencing both the exothermic reaction and the melt ejection mechanics. The specific system investigated utilizes a 1 kW fiber laser, representing a common low-to-medium power source widely deployed in sheet metal workshops.

Previous research has established general trends relating cutting speed and thickness [1], often utilizing dimensionless numbers or generalized empirical models [4,8]. However, a significant gap remains in establishing an explicit, localized parameter–thickness relationship model that couples the primary variable parameters—Cutting Speed (V) and Focus Position (FP)—specifically for this fixed-power, air-assisted fiber laser configuration [10].

Therefore, the aim of this research is twofold: (1) to empirically derive accurate mathematical models describing the relationships between material thickness (t) and the optimal operational parameters (V and FP); and (2) to provide a robust empirical basis for a subsequent computational study designed to validate the physical phenomena governing the process. The empirical models presented herein serve as essential predictive tools for process control and are integral for calibrating the thermal boundary conditions in numerical simulations [3].

The remainder of this paper is structured as follows: Section 2 details the experimental setup and methodology, Section 3 presents the derived empirical models and their goodness of fit, Section 4 discusses the physical implications of these models, and Section 5 provides the conclusions and outlines the future scope for computational validation.

II. METHODOLOGY

The empirical phase of this study was strictly focused on determining the maximum cutting speed and corresponding optimal process parameters required to achieve a clean cut through different thicknesses of mild steel plate using a 1 kW fiber laser system with air assistance.

A. Experimental Setup and Equipment

The experiments were performed on a commercially available laser cutting system equipped with the following specifications:

- Laser Source: Continuous Wave (CW) Fiber Laser with a nominal power of P_max = 1000 W (1 kW).
- Wavelength: Approximately 1070 nm (near-infrared).
- Workpiece Material: Commercial Grade Mild Steel with thicknesses ranging from 0.3 mm to 4.0 mm.
- Assist Gas: Compressed Air, regulated by a high-pressure valve system.

The key operational parameters that were kept constant throughout the experiment to isolate the thickness dependency were Laser power that is set to 100% (Nominal to 1kW) and Gas pressure at the value of 15 bar. A high, constant pressure selected to maximize melt ejection force [10]. The laser power was adjusted to 100% to give absolute maximum performance.

B. Experimental Procedure

The procedure involved a systematic determination of the maximum operational window for each specified material thickness:

- Thickness Selection: A specific thickness (t) of mild steel plate was mounted.
- Nozzle Diameter Selection: An appropriate nozzle diameter (e.g., 1.5S, 2.0S, 3.0S) was selected, guided by standard manufacturing guidelines to ensure effective gas flow and melt evacuation for the given thickness [8, 11].
- Focus Position Search: The Focus Position (FP) was iteratively adjusted to find the depth that yielded the narrowest kerf and the cleanest cut (minimal dross). The FP is reported as the distance from the material surface, with negative values indicating the focus is below the surface.
- Maximum Speed Determination: With the optimal FP fixed, the Cutting Speed (V) was systematically increased until the cut was deemed unsuccessful (loss of cut or severe dross). The maximum speed just prior to failure that still produced an acceptable clean cut was recorded.

The resulting dataset is presented in Table 1.

Table 1 Experimental Data Defining the Boundary of Maximum Cutting Performance.

Thickness (mm)	Speed (m/min)	Focus Position (mm)	Nozzle Diameter	Gas Pressure (bar)	Power (%)
0.3	35	-1.0	1.5S	15	100
0.5	25	-1.0	1.5S	15	100
0.8	20	-1.0	1.5S	15	100
1.2	14	-1.5	1.5S	15	100
1.8	4	-1.5	2.0S	15	100
2.0	3	-2.0	2.0S	15	100
3.0	3	-2.5	2.0S	15	100
4.0	1	-5.0	3.0S	15	100

C. Empirical Modeling with AI

The collected data was modeled using linear regression on transformed variables [3]. Power law model is established with exponential decay model and Linear Focus Position Model. Artificial intelligence platform is used to do mathematical and empirical modelling of the data and the results are as shown below:

- Power Law Model: $V = a \cdot t^{b}$, tested via the linear form $\ln(V) = \ln(a) + b \cdot \ln(t)$.
- Exponential Decay Model: $V = a \cdot e^{(b \cdot t)}$, tested via the linear form $\ln(V) = \ln(a) + b \cdot t$.
- Linear Focus Position Model: $FP = c \cdot t + d$.

III. RESULTS AND EMPIRICAL MODELLING

A. Maximum Cutting Speed vs. Thickness

Both the Power Law and Exponential Decay models successfully captured the steep, inverse relationship between cutting speed and thickness. The comparative results are summarized in Table 2.

Table 2 Regression Results for Speed vs. Thickness

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Model Type	Equation	Parameter a	Parameter b	R^2
Power Law	$V = a.\ t^b$	10.082	-1.364	0.9132
Exponential Decay	$V = a\ .\ exp^{(b\ .\ t)}$	37.097	-0.950	**0.9206**

The Exponential Decay Model exhibited a slightly higher R-squared value, indicating a better empirical fit to the experimental data. The finalized empirical model for maximum cutting speed is: $V = 37.097\ .\ exp^{(-0.950\ *\ t)}$

B. Optimal Focus Position vs. Thickness

The relationship between the optimal Focus Position (FP) and the material thickness (t) was modeled using a simple linear regression.

The fitted linear trend is shown alongside the experimental data points in the Figure 1 below.

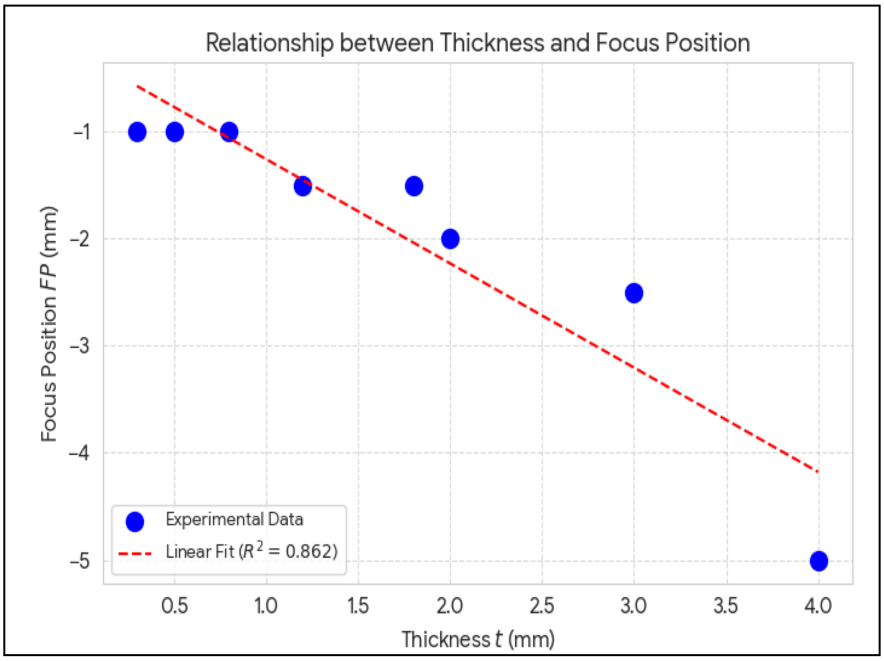

Fig 1 Relationship Between Thickness and Optimal Focus Position. The Plot Shows a Strong Linear Trend (Dashed Red Line) Correlating the Two Parameters.

The resulting linear model is: $FP = c\ .\ t + d$

The regression yielded the following constants:

- Slope (c): -0.975
- Y-intercept (d): -0.280
- Coefficient of Determination (R^2): 0.8623

The empirical relationship for optimal focus position is:

$$FP = -0.975\ .\ t - 0.280$$

IV. DISCUSSION

A. Physical Interpretation of the Speed Model

The dominant Exponential Decay in cutting speed confirms the physical limitations of the thermal process. The laser energy must heat and melt an ever-increasing volume of material (t) per unit length, while also overcoming the heat losses due to conduction into the bulk material. The exponential form suggests that increasing thickness rapidly raises the energy per unit length required for full penetration, a finding consistent with fundamental thermal models of laser processing [8, 4]. The constant a = 37.097 m/min can be interpreted as the theoretical maximum speed for an infinitely thin sheet, while the coefficient b = -0.950 quantifies the severity of the thickness penalty imposed by the fixed 1 kW power source.

B. Role of Focus Position and Melt Ejection

The highly correlated negative linear trend for the optimal focus position ($FP \approx -1\ .\ t$) is a critical finding for process control [3.2]. It physically indicates that to maintain the required power density and a clear melt path:

- For thin materials ($t < 1.2$ mm), the focus is kept near the surface ($FP \approx -1.0$ mm) to concentrate energy at the point of ignition.
- For thicker materials ($t > 1.2$ mm), the focus must be moved deep inside the material to maintain the beam waist within the cut front, ensuring consistent energy absorption throughout the entire thickness.

This strategy also accounts for the necessary accompanying changes in Nozzle Diameter (1.5S -> 3.0S), which increases with thickness to facilitate the removal of a larger volume of molten material by the 15 bar air assist gas jet [8,10].

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V. CONCLUSION

The empirical modelling successfully established quantifiable relationships between the material Thickness and the two most critical operational parameters: Cutting Speed (V) and Focus Position (FP) for a 1 kW fiber laser using air assist.

- Cutting Speed is Governed by Exponential Decay: The maximum speed follows the relationship $V = 37.097 * \exp^{(-0.950 \cdot t)}$, confirming the exponential nature of the energy requirement necessary to achieve full penetration across increasing thickness ($R^2 = 0.9206$).
- Linear Strategy for Focus Position: The optimal focus position is accurately modelled by a negative linear function, $FP = -0.975 \cdot t - 0.280$, indicating that the focus point must be lowered approximately 1 mm for every 1 mm increase in thickness to optimize energy delivery and melt removal ($R^2 = 0.8623$).

The derived empirical models provide a robust foundation for the computational component of the study, offering precise equations for setting both the cutting speed and the focus position across the range of mild steel thicknesses under constant power and air-assist pressure.

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