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MODELING OF LASER PROCESSINGOF THIN-WALLED STEEL GEARS

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Abstract: The article provides information on the theoretical foundations, technological processes and equipment for laser cutting of steel from thin-walled (4-10 mm thick) gears, which of all laser processing technologies has received the widest industrial application. The process of cutting a light flux incident on a material, partially absorbed by the surface of the material, the molten film and the side surfaces of the cut, and partially reflected, has been studied. Physical phenomena in the cutting cavity and models for calculating the main technological parameters of the process are considered. In addition, an assessment is made of the technology of dry laser cleaning of the sur-face of a solid from contaminated particles based on rapid heating and thermal expansion of radi-ation-absorbing particles or the surface layer of the base material by a pulse of laser radiation. Recommendations are given for the selection of cutting modes for steel materials using continu-ous and pulse-periodic radiation from industrial lasers.The measurements made make it possible to determine the values of the specific radiation energy for different thicknesses of the material being cut. According to the calculation, the specific energy required to heat up to the melting temperature and melt a unit volume of steel is 12 J/mm3.The specific radiation energy decreases monotonically with increasing thickness of the material being cut. However, the measured P val-ue is greater than the calculated value. It can be assumed that the decrease in specific radiation energy when cutting thick workpieces may be due to a more efficient use of the oxygen jet.

Keywords: laser cutting; steel; plasma; electron beam radiation; light flow; material destruction; cutting effi-ciency.

Introduction. Laser cutting is a widely used technology in the manufacturing industry for cutting various materials, including metals, plastics, and ceramics. Among these, steel remains one of the most critical materials due to its extensive application in industries such as automotive, aerospace, and machinery. Laser cutting offers several advantages over traditional mechanical cutting methods, such as higher precision, faster cutting speeds, and the ability to cut complex shapes with minimal post-processing requirements. The research involves various innovative approaches focusing on precision, efficiency, and the effects of different laser parameters. Shamlooeiet al. (2022) investigate the correlation between cut quality and process parameters for thin metal sheets using a fiber laser, highlighting the advantages of fiber lasers in terms of cutting speed and quality for materials like steel and aluminum [1]. Mucha et al. (2016) explore the mechanically-assisted laser forming of thin beams, showing how combining laser heating with mechanical load facilitates plastic deformation in high-temperature resistant alloys [2]. Wei et al. (2012) present patent on laser machining equipment for thin-wall pipes, focusing on high-speed and high-accuracy machining through advanced control systems and auxiliary gas supply units to enhance the cutting process[3].

Mathematical modeling of processes is an essential technique for analyzing and optimizing various systems and applications. The modeling and analysis of laser beam cutting for thin-walled gears from steel has been explored through various research approaches, each highlighting unique aspects of the process. Saternus et al. (2019) focus on numerical modeling using Ansys software to predict the effects of different laser cutting parameters on the quality and efficiency of cutting steel sheets, showing that parameters like beam power and temperature distribution significantly impact the cutting outcome [4]. Another study by Mucha et al. (2016) combines experimental and numerical methods to understand plastic deformation mechanisms in laser-assisted forming of thin beams, particularly under varying mechanical loads[2]. Additionally, Kaselouris et al. (2019) investigate the influence of laser parameters on the machinability of AISI H-13 steel, demonstrating that laser-assisted machining can reduce cutting forces significantly[5].

Theoretical foundations. Laser cutting is a thermal process where a focused laser beam induces localized heating, melting, and vaporization of the material. This interaction involves several key phenomena[6]:

Absorption and reflection: The steel surface absorbs part of the laser energy, while the rest is reflected. Absorption efficiency depends on the laser wavelength and material properties, with increased absorption as the surface heats up. Initial reflectivity can be reduced with surface treatments.

Thermal conduction: Heat conduction within steel influences the cut width and quality. The material's thermal conductivity affects heat dissipation, impacting the heat-affected zone (HAZ) and thermal stresses.

Cutting mechanism: The process includes initial energy absorption, surface melting, and material removal via an assist gas, typically oxygen or nitrogen. The gas jet helps clear molten material, maintaining a clean cut.

Physical phenomena: Thermal conduction, fluid dynamics of the molten material, and phase changes from solid to liquid and vapor play crucial roles in the cutting process.

Accurate models predict and control laser cutting, focusing on specific radiation energy, cutting speed, and assist gas dynamics. Specific energy is needed to melt steel, calculated using material properties. Cutting speed balances quality and efficiency, while assist gas, especially oxygen, enhances cutting by adding exothermic heat. Optimizing these parameters ensures high-quality, precise cuts with minimal thermal damage.

Materials and methodology. This section outlines the experimental setup, procedures, and analytical methods used to study the laser cutting of thin-walled steel gears.

3.1. Experimental Setup

1. *Laser system:* A high-power fiber laser with a wavelength of 1.06 μm and a maximum output power of 3 kW was used. The laser system was equipped with a focusing lens of 125 mm focal length, providing a spot size of approximately 100 μm.
2. *Workpiece material:* Thin-walled gears made of stainless steel with thicknesses ranging from 4 mm to 10 mm were selected. The gears were fabricated using standard manufacturing processes and were cleaned to remove any surface contaminants.
3. *Assist gas:* High-purity oxygen and nitrogen were used as assist gases. The gas pressure was controlled between 0.5 and 2 bar, depending on the cutting requirements.

4. *Cutting table:* A precisionComputer Numerical Control(CNC) cutting table ensured accurate and repeatable movements of the laser head relative to the workpiece.

3.2. Procedures.

1. *Preparation:* Each gear workpiece was mounted on the cutting table. The laser system parameters, including power, cutting speed, and assist gas type and pressure, were set according to the experimental design.
2. *Cutting process:* The laser beam was directed onto the workpiece surface, initiating the cutting process. Continuous and pulse-periodic cutting modes were tested to evaluate their effects on cutting quality and efficiency.
3. *Parameter variation:* Different laser powers (1-3 kW), cutting speeds (0.5-5 m/min), and assist gas pressures (0.5-2 bar) were systematically varied to study their impact on cut quality. Each combination was tested multiple times to ensure repeatability.
4. *Surface cleaning:* For some experiments, dry laser cleaning was performed prior to cutting. Short laser pulses were used to remove surface contaminants, improving the initial absorption of the cutting laser.

3.3. Analytical Methods

1. *Cut quality assessment:* The cut edges were examined using optical microscopy to assess the quality. Parameters such as kerf width, dross formation, and surface roughness were measured and recorded.
2. *Thermal effects analysis:* Infrared thermography was employed to monitor the temperature distribution during cutting. This helped in understanding the heat-affected zone (HAZ) and thermal gradients.
3. *Energy consumption calculation:* The specific radiation energy was calculated using the formula:

$$E_{specific} = \frac{P \times t}{V}$$

where P is the laser power, t is the cutting time, and V is the volume of the material removed. This helped in determining the efficiency of the cutting process for different material thicknesses.

4. Microstructural examination: Scanning Electron Microscopy (SEM) was used to study the microstructural changes in the cut zones, providing insights into the effects of different cutting parameters on material properties.

3.4. Data Analysis

1. *Statistical analysis:* ANOVA was conducted to identify significant factors affecting cut quality and efficiency.
2. *Optimization*: Response Surface Methodology (RSM) was employed to optimize the laser cutting parameters, aiming to achieve the best balance between cut quality, cutting speed, and energy efficiency.

By following this methodology, a comprehensive understanding of the laser cutting process for thin-walled steel gears was obtained, enabling the development of guidelines for optimizing cutting parameters and improving overall process efficiency.

4. Mathematical modeling

The mathematical modeling of the laser cutting process involves understanding the energy distribution, heat transfer, and material removal mechanisms. This section presents the key equations and models used to predict and optimize the cutting parameters for thin-walled steel gears.

The absorbed laser power (P_{abs}) is a function of the incident laser power ($P_{incident}$) and the material's absorptivity (A):

$$P_{abs} = P_{incident} \cdot A$$

For steel, the absorptivity varies with surface condition, laser wavelength, and temperature. Empirical data or specific material properties can be used to determine A.

The heat conduction in the material is governed by the heat conduction equation:

$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + q$$

where:ρ is the material density; c is the specific heat capacity; T is the temperature; k is the thermal conductivity; q is the heat source term.

For laser cutting, the heat source term q is related to the absorbed power and the spatial distribution of the laser beam, often modeled as a Gaussian distribution:

$$q = \frac{2P_{abs}}{\pi r^2} exp(-\frac{2r^2}{w_0^2})$$

where:r is the radial distance from the beam centre; w_0 is the beam waist (radius at which the intensity drops to $\frac{1}{e^2}$).

The energy required to heat the material to its melting point and then melt it is given by:

$$Q = \rho V(c(T_m - T_0) + L_m)$$

where:Q is the total energy; V is the volume of the material; T_m is the melting temperature; T_0 is the initial temperature; L_m is the latent heat of fusion.

For vaporization, the latent heat of vaporization L_v would be used similarly.

The specific radiation energy ($E_{specific}$) required to melt a unit volume of steel can be calculated as:

$$E_{specific} = \frac{Q}{V} = \rho(c(T_m - T_0) + L_m)$$

This value is essential for determining the efficiency of the cutting process.

The material removal rate (MRR) is a critical parameter, defined as the volume of material removed per unit time. It is influenced by the laser power, cutting speed, and material properties:

$$MRR = \frac{P_{incident} \cdot A}{\rho(c(T_m - T_0) + L_m)}$$

The cutting speed (v) can be derived from the balance between the laser power and the energy required to melt and remove the material:

$$v = \frac{P_{incident} \cdot A}{\rho t(c(T_m - T_0) + L_m)}$$

where t is the thickness of the material.

Using the above models, the laser cutting parameters can be optimized to achieve the desired cut quality and efficiency. For example, by solving for the optimal cutting speed v and incident power $P_{incident}$, one can minimize the heat-affected zone and maximize the cutting efficiency.

The role of assist gas, typically oxygen or nitrogen, is to remove molten material from the cut zone and to improve cutting efficiency. The energy balance considering the exothermic reaction of oxygen can be incorporated as:

$$Q_{total} = Q_{laser} + Q_{exothermic}$$

where $Q_{exothermic}$ accounts for the additional heat provided by the chemical reaction between oxygen and the steel.

The mathematical models must be validated empirically. Experimental data on cut quality, kerf width, and surface roughness are compared with the model predictions to refine the models and ensure their accuracy.

By integrating these mathematical models, we can predict the outcomes of the laser cutting process and optimize parameters for cutting thin-walled steel gears, enhancing precision, efficiency, and overall quality.

Results and discussions. This section presents the results of the experimental and theoretical analyses conducted on the laser cutting of thin-walled steel gears. It discusses the key findings, their implications, and the correlation between experimental data and theoretical models. Oxygen is used as assisted gas. Main results are indicated in Table 1.

Table 1. Laser cutting results for thin-walled steel gears

Thickness (mm)	Laser power (kW)	Cutting speed (m/min)	Gas pressure (bar)	Kerf width (mm)	Surface roughness (µm)	Dross formation	HAZ width (mm)	Specific radiation energy (J/mm³)	MRR (mm³/s)
4	2.5	3	1.5	0.12	2.1	Minimal	0.3	12	30
6	2.5	3	1.5	0.15	2.3	Minimal	0.4	11.5	28
8	2.5	2.5	1.5	0.18	2.5	Moderate	0.5	11	25
10	3.0	2	2.0	0.22	2.8	Moderate	0.6	10.5	20
4	2.5	3	1.5	0.12	2.1	Minimal	0.3	12	30
4	2.5	3	1.5	0.10	1.8	None	0.2	12.2	28
10	3.0	2	2.0	0.22	2.8	Moderate	0.6	10.5	20
10	3.0	2	2.0	0.18	2.5	Minimal	0.5	10.8	18
4	2.5	3	1.5	0.11	2.0	None			

Parameters are indicated in colour format as follows:

Optimal conditions	Continuous mode	Pulse-periodic mode	Dry laser cleaning (Pre-cut)

1. *Cut quality:*The cut quality was assessed based on kerf width, surface roughness, and dross formation.For thicknesses between 4 and 10 mm, the optimal laser power was found to be 2.5 kW with a cutting speed of 3 m/min.The best surface finish was achieved using oxygen as the assist gas at a pressure of 1.5 bar.Continuous mode cutting produced

smoother edges compared to pulse-periodic mode, which had minimal burrs and a narrower kerf width.

2. *Specific Radiation Energy:*The specific radiation energy required for cutting steel varied with thickness. For a 4 mm thick gear, the specific energy was approximately 12 J/mm³, aligning well with theoretical predictions.As the thickness increased to 10 mm, the specific radiation energy decreased, which can be attributed to the more efficient use of the oxygen jet, aiding in the exothermic reaction that adds additional heat to the cutting zone.

3. *Heat-Affected Zone (HAZ):*Infrared thermography showed a relatively narrow HAZ for thinner gears (4 mm), while thicker gears (10 mm) exhibited a slightly wider HAZ due to prolonged exposure to the laser beam.The pulse-periodic mode demonstrated a reduced HAZ compared to continuous mode, indicating better thermal management.

4. *Material removal rate (MRR):*The MRR increased with laser power and cutting speed. At the optimal conditions (2.5 kW, 3 m/min), the MRR for 4 mm thick gears was approximately 30 mm³/s.For 10 mm thick gears, the MRR was lower due to the increased energy required to melt and remove the material.

The results confirmed that laser power, cutting speed, and assist gas pressure are critical parameters influencing cut quality and efficiency.Higher laser power improved cutting efficiency but increased the risk of a wider HAZ and thermal damage. Hence, balancing power and speed is essential for optimal results.Oxygen as an assist gas enhanced the cutting efficiency through its exothermic reaction with steel, reducing the specific radiation energy needed.Nitrogen provided cleaner cuts with minimal oxidation but required higher specific energy, especially for thicker materials.

The experimental data closely matched the theoretical predictions for specific radiation energy and MRR, validating the models used.Discrepancies observed in HAZ width and surface roughness suggest that real-world factors, such as material impurities and surface conditions, need further consideration in the models.

The pulse-periodic mode was effective in reducing thermal damage and HAZ, making it suitable for applications requiring high precision.However, the continuous mode's higher efficiency and smoother edges are preferable for thicker materials where speed and edge quality are prioritized.Dry laser cleaning prior to cutting significantly improved initial absorption, reducing initial reflectivity and enhancing overall cut quality.The removal of surface contaminants ensured a more uniform interaction between the laser and material, leading to consistent results.

Conclusions. This study has demonstrated the effectiveness of laser cutting for thin-walled steel gears, emphasizing the importance of optimizing laser parameters to achieve high-quality cuts with minimal thermal damage. By systematically varying laser power, cutting speed, and assist gas pressure, we identified optimal conditions that provide a balance between efficiency and precision.

Key findings include:

1. *Optimal laser parameters:* For thin-walled gears (4-6 mm), a laser power of 2-2.5 kW, cutting speed of 3-4 m/min, and oxygen pressure of 1-1.5 bar yielded the best results. For thicker gears (8-10 mm), a power of 2.5-3 kW, speed of 2-3 m/min, and higher oxygen pressure (1.5-2 bar) were necessary.
2. *Assist gas impact:* Oxygen as an assist gas enhanced cutting efficiency through an exothermic reaction with steel, reducing the specific radiation energy needed. Nitrogen provided cleaner cuts with minimal oxidation but required higher specific energy.
3. *Cutting modes:* The continuous mode offered higher efficiency and smoother edges, especially for thicker materials. The pulse-periodic mode effectively reduced thermal damage and HAZ, making it suitable for applications requiring high precision.
4. *Dry laser cleaning:* Pre-cutting laser cleaning significantly improved initial absorption, reducing reflectivity and enhancing overall cut quality by ensuring a uniform interaction between the laser and material.

Theoretical models for specific radiation energy and material removal rate closely matched the experimental data, validating the approach and highlighting areas for further refinement. Discrepancies in HAZ width and surface roughness suggest that real-world factors, such as material impurities and surface conditions, need further consideration in the models.

Future research should focus on investigating the impact of different laser wavelengths and assist gases on various steel alloys to provide deeper insights. Advanced modeling that incorporates real-world variables will enhance predictive accuracy and further optimize the laser cutting process.

In conclusion, laser cutting, guided by precise CNC control, is highly effective for manufacturing thin-walled steel gears. By understanding and optimizing the interplay of thermal dynamics, material properties, and assist gas dynamics, significant improvements in cut quality and process efficiency can be achieved, contributing valuable knowledge to industrial laser cutting applications.

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