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Analysis of the influence of defocused laser beam on uneven material surface processing based on mathematical model and simulation approach

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Abstract
Laser-processing technology has advanced precision surface material processing, but challenges remain in maintaining the laser beam waist position on uneven surfaces. Surface irregularities cause defocus and non-perpendicular alignment leading to distortions in beam spot size and shape, which reduce processing quality. This study develops a mathematical model and simulation framework to analyze beam waist positioning errors during surface processing. Using MATLAB Partial Differential Equation (PDE) and finite element method, the simulation evaluates how variables like laser incidence angle and focal distance affect beam spot characteristics. Results reveal that defocus and misalignment enlarge and distort the laser beam spot, with higher incidence angles causing elliptical deformation. The simulation is critical in advancing the understanding of laser-material interactions under suboptimal conditions such as defocus and misalignment. It provides critical insights into the geometrical of laser beam, enabling the development of precise error detection methods for beam spot irregularities. Furthermore, these findings lay the groundwork for designing adaptive mechanisms that enhance the precision and reliability of laser-based surface material processing, addressing challenges posed by uneven workpiece surfaces. This approach aims to optimize laser processing quality and expand its applicability in high-precision manufacturing.

Keywords
laser processing technology, defocus laser beam, mathematical model, simulation of laser beam spot, laser beam spot geometry, beam projection on the surface, material surface processing

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Математический и имитационный анализ влияния расфокусировки лазерного пучка на процесс обработки неровной поверхности

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Аннотация
Введение. Технология лазерной обработки позволила повысить точность обработки поверхности заготовки. При этом сохраняются проблемы, связанные с поддержанием положения перетяжки пучка на неровных поверхностях. Неровности поверхности вызывают расфокусировку и неперпендикулярное выравнивание, что приводит к искажениям размера и формы лазерного пятна, снижающим качество обработки. **Метод.** Разработана математическая модель и схема моделирования для анализа ошибок позиционирования лазерного пучка при обработке поверхностей. Используя средства решения дифференциальных уравнений MATLAB и метод конечных элементов, моделирование позволило рассчитать величины изменения угла падения лазерного излучения и фокусного расстояния, влияющие на характеристики проекции луча на поверхность. **Основные**

результаты. Полученные результаты показывают, что расфокусировка и несоосность увеличивают и искажают проекцию пучка на поверхность, а большие углы падения вызывают эллиптическую деформацию. **Обсуждение.** Моделирование имеет решающее значение для понимания взаимодействия лазерного излучения и материала в неоптимальных условиях, таких как расфокусировка и несоосность. Оно дает критическое представление о геометрических искажениях лазерного пучка, позволяя разработать точные методы обнаружения ошибок проекции пучка на поверхность. Кроме того, эти результаты закладывают основу для разработки адаптивных механизмов, повышающих точность и надежность лазерной обработки поверхности материала и решающих проблемы, связанные с неровной поверхностью заготовок. Этот подход направлен на оптимизацию качества лазерной обработки и расширение ее применимости в высокоточном производстве.

Ключевые слова
технология лазерной обработки, расфокусировка лазерного пучка, математическая модель, моделирование, геометрическая форма лазерного пятна, проекция пучка на поверхность, обработка поверхности материала

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Introduction

In recent years, laser-processing technology has been widely developed with the aim of solving various needs, especially in surface material processing and micromachining. This is inseparable from the advantages of laser-processing, namely, high flexibility of processing, high processing accuracy, non-contact processing, strong adaptability of processing materials, and high energy density. In addition, the main advantage of laser processing that cannot be achieved by conventional machining technology is that laser processing technology makes it possible to process materials on a micro scale or commonly referred to as micromachining. Because of these advantages, laser-processing technology is widely applied to various surface material processing, such as annealing [1]; ablation [2–4]; marking [5]; texturing [6–9]; etching [10, 11]; patterning [12]; and polishing [13, 14].

Surface material processing is a material processing that requires a high level of accuracy or commonly referred to as high precision machining. In laser processing, high precision machining is greatly influenced by the distance between the laser focus (beam waist) and the surface of the material or workpiece being processed. During laser processing, it is very important to ensure the stability of the focus beam waist position right on the surface of the material or workpiece. This is because an unstable focus beam position or defocus will cause the laser energy density in the irradiated area to be unstable and reduce the precision and quality of the material or workpiece being processed [15]. But in reality maintaining the stability of the focus beam position in laser processing is not something that is easy in material processing, especially micromachining and surface material processing.

The main factor that causes laser defocus in surface processing is the uneven surface of the material or workpiece. Uneven surfaces result in the angle of laser beam incidence not being perpendicular to the material being processed, which results in changes in the shape and size of the laser beam spot thereby reducing the intensity of the laser energy. It is also known that the greater the inclination of the laser beam angle to the surface of material or workpiece, the wider the irradiated area will be and the intensity of the laser energy will also decrease [16]. Therefore, to be able to solve the problem of laser defocus and to maintain the stability of the focus beam on the uneven surface of the workpiece, research is needed on the development of laser beam position error compensation methods, especially in surface processing materials.

Several studies have explored methods to optimize laser processing and minimize distortions. Research [17] investigated how laser scanning patterns influence residual stress and distortions in laser-processed components, emphasizing that proper beam path control significantly improves dimensional accuracy. Research [18] introduced a Digital Micromirror Device for beam shaping, demonstrating that optimized beam control can reduce thermal distortions. However, while these studies focus on beam shaping and scanning, they do not directly address the effects of a defocused laser beam on uneven surfaces.

In the field of laser welding and bending, distortion remains a critical issue. Research [19] developed a model to predict residual stresses and distortions in Laser Beam Welding of aluminum lap joints, showing how thermal effects influence stress distribution. Similarly, research [20] studied edge effects and longitudinal distortions in the laser bending process, revealing how uneven heat distribution leads to deformation inaccuracies. Research [21] expanded this investigation by examining nonconventional laser beam geometries and their impact on stress distribution in laser bending of tubes. These studies collectively highlight the thermal effects of laser processing, but they focus on structured materials rather than surface processing of uneven materials.

More relevant to defocused laser beam effects, research [22] introduced a hybrid model that integrates Monte Carlo simulations and Shack-Hartman wavefront sensing to analyze laser beam distortion. Their approach provides a foundation for understanding how beam deviations affect processing accuracy. While these studies explore beam deviations and correction strategies, they primarily focus on beam optimization; they did not specifically analyze the effects of defocused laser beam on uneven surfaces.

Given this gap in existing research, in this study, a comprehensive mathematical model and simulation framework are proposed to investigate the characteristics of laser beam spots during material surface processing, particularly under conditions where positioning errors, such as defocus and non-perpendicular alignment, occur. The developed model provides a detailed analysis of how these errors affect critical parameters, including the size and shape of the laser beam spot on uneven material surfaces. By incorporating factors such as the laser incidence angle and focal distance, the simulation evaluates the impact of surface irregularities on processing accuracy and quality.

The findings from this study can also serve as a foundation for future research aimed at developing compensation mechanisms to correct laser beam spot defocused. By leveraging the insights gained from the mathematical model and simulation results, future work can explore strategies to improve machining precision and mitigate the effects of beam defocused on material processing quality.

Laser Beam Positioning Errors on Material Surface Processing

Material surface processing, commonly known as high-precision machining, demands an exceptional level of accuracy. In the realm of laser processing, achieving high precision is intricately linked to the precise distance between the laser focus (beam waist) and the surface of the material or workpiece undergoing precise. The beam waist, also referred to as laser focus or focus beam, designates the region where the laser beam is at its most constricted, exhibiting a minimal beam radius [23]. Ensuring the stability of the beam waist position precisely on the material or workpiece surface is paramount during laser processing. An unstable focus or beam waist position or defocus can result in fluctuating laser energy density in the irradiated area, subsequently compromising the precision and quality of the processed material or workpiece. Two types of defocus are observed in laser processing: positive and negative defocus. Positive defocus occurs when the laser beam focuses above the workpiece or material surface, aligning with the position of the focus beam. Conversely, negative defocus transpires when the focus is below the workpiece or material surface, or the focus beam is positioned beneath it. For a detailed visual representation, refer to Fig. 1.

Ensuring the stability of the beam waist position in laser processing proves to be a challenging endeavor, particularly in material processing realms such as micromachining and surface material processing. The primary culprit inducing laser defocus in surface processing is the irregularity of the material or workpiece surface. These uneven surfaces disrupt the perpendicular alignment of the laser beam incidence to the material being processed, triggering alterations in the shape and size of the laser beam spot and consequently diminishing the overall intensity of the laser energy. It is further established that a higher inclination of the laser beam angle to the material or workpiece surface leads to a broader irradiated area accompanied by a concurrent reduction in the intensity of the laser energy. For more details please refer to Fig. 2.

To effectively address the challenges of laser defocus and ensure the stability of the focus beam on uneven material or workpiece surfaces, dedicated research is essential for developing laser beam position error compensation methods, particularly tailored for surface processing materials. Confronting issues arising from dynamic nature of the laser beam spot characterized by fluctuations in shape, size, or errors on irregular materials or workpieces surfaces, demands the implementation of a method that ensures the steadfast stability. In the context of this study, an innovative method is currently under development, featuring adaptive capabilities within the laser beam system. This method empowers the laser to dynamically adapt to the ever-changing materials or workpieces surfaces, ensuring a consistently perpendicular orientation as shown in Fig. 3.

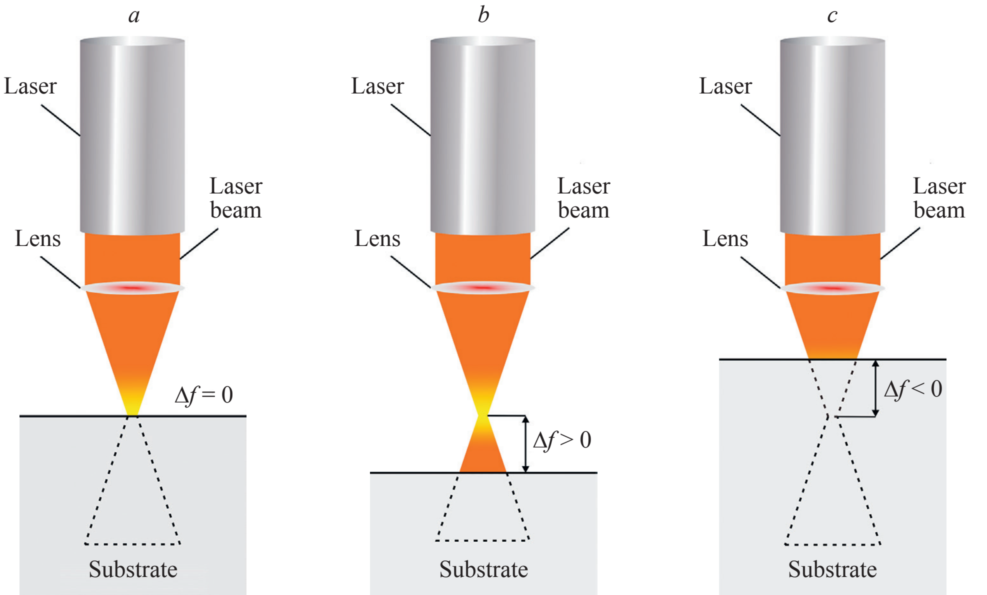

Fig. 1. Scheme of focus and defocus beam position in laser processing: focus (*a*); positive defocus (*b*); negative defocus (*c*); Δf is the distance between the beam waist and the material surface

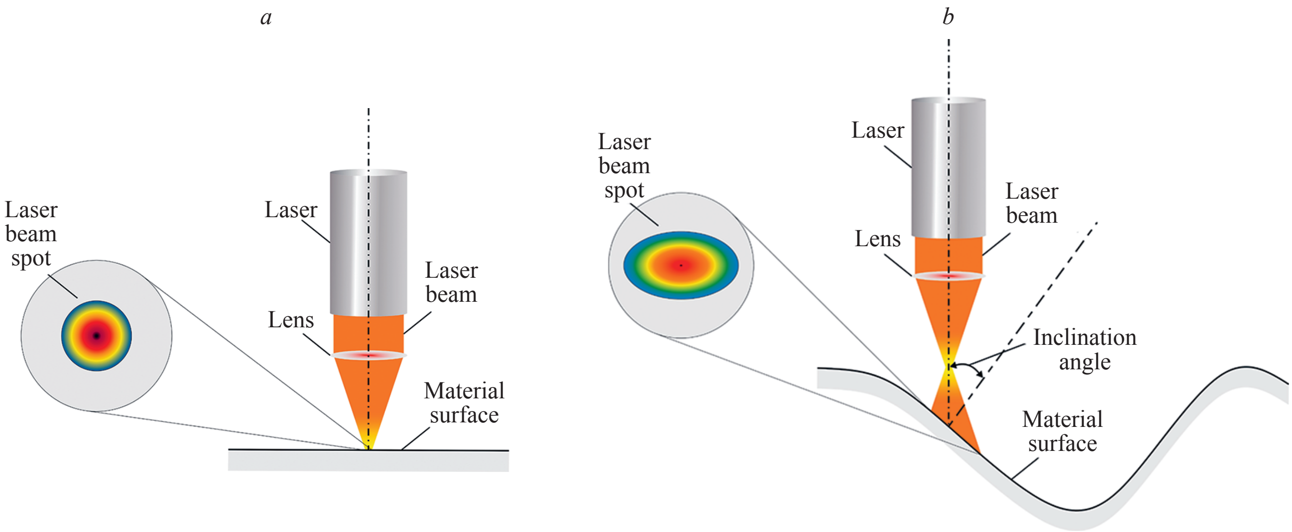

Fig. 2. Scheme of laser beam spot on material processing with: even/flat material surface and perpendicular beam — focus laser beam spot with round shape and high laser energy intensity (*a*); uneven material surface and inclined beam — defocus laser beam spot with eclipse shape and low laser energy intensity (*b*)

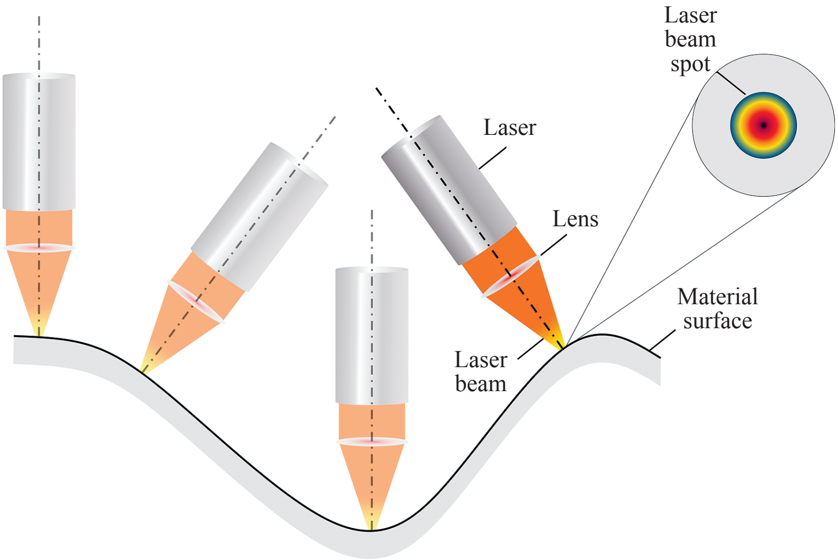

Fig. 3. Conceptual framework for an adaptive laser system designed to stabilize the focus of laser beams and compensate for positioning errors on uneven material surfaces

Such adaptability not only maintains precise beam waist positioning but sustains it with meticulous accuracy throughout the entire laser processing procedure. Consequently, the proposed method stands as a promising solution to either eliminate or compensate for laser beam position errors during material surface processing.

Mathematical Model of Laser Beam Positioning Errors on Material Surface Processing

A mathematical model serves as a systematic approach for representing and elucidating real-world systems and phenomena by employing mathematical formulas and descriptive methodologies. Within the scope of this study, the mathematical model is designed to meticulously investigate, analyze, and forecast the behavior of a laser beam when interacting with both uneven and inclined surfaces of a material. The primary objective is to rectify or eliminate positional errors exhibited by the laser beam on the material's surface, thereby enhancing precision and eliminating discrepancies in its positioning.

Laser beam exhibits a strong correlation with Gaussian beams [24]. This connection arises from the fact that the majority of lasers are engineered to function in the lowest transverse mode known as Gaussian beams. This deliberate design choice aims to achieve the most focused beam possible, a critical factor in applications like material processing. Consequently, the mathematical modeling undertaken in this study is grounded in the principles of Gaussian beam modeling.

The mathematical model employed in this study is rooted in the surface heat source model outlined in reference [16]. The primary objective of this model is to elucidate the distribution of energy intensity across irregular or inclined material surfaces. Understanding the intricacies of the laser beam spot surface heat source model allows for insight into how uneven or inclined material surface influences the laser beam spot shape, size, and energy intensity. Illustration in Fig. 4 is a schematic representation of the laser beam interacting with the material surface. Here, α denotes the incidence angle of the laser beam due to the inclined surface, h represents the distance to the focal plane or laser beam focus, and $w(z)$ indicates the radius where intensity values decrease to $1/e^2$ of their axial values. Additionally, w_0 signifies the radius of the laser beam focus or beam waist radius, while θ represents the divergence half-angle.

In order to ascertain the intensity distribution of the laser beam spot on the material perpendicular surface, mathematical equations are utilized. Within this framework, the parameter w_1 represents the laser beam radius specifically on the perpendicular surface – 1 (defocus).

$$q_1(x, y) = q_{axis}\exp\left[-2\left(\frac{x^2+y^2}{w_1^2}\right)\right], \qquad (1)$$

where q_{axis} is the on-axis intensity value. Obtaining the total power in the laser beam is determined by applying equation:

$$P\eta = q_{axis}\int_{-a_y}^{a_y}\int_{-a_y}^{a_x}\exp\left[-2\left(\frac{x^2+y^2}{w_1^2}\right)\right]dxdy, \qquad (2)$$

where $P\eta$ is the power or energy of the laser beam within a specific area.

By merging equations (1) and (2), the resulting heat source model aligns with the formulation presented in the following equation:

$$q_1(x, y) = \frac{2P\eta}{\pi w_1^2}\exp\left[-2\left(\frac{x^2+y^2}{w_1^2}\right)\right]. \qquad (3)$$

The value of w_1 from equation (3) is obtained using the following equation:

$$w_1^2 = w_0^2 + \theta^2 h^2. \qquad (4)$$

Meanwhile, the intensity distribution of the laser beam spot on the inclined surface of the material can be determined by consulting the following equation:

$$q_2(x, y, z) = q_{axis}\exp\left[-2\left(\frac{x^2+y^2}{w_2^2(z)}\right)\right]. \qquad (5)$$

The laser beam radius on the inclined surface — 2 (defocus), denoted as w_2, is defined by the equation below which has the same principle with the equation (4).

$$w_2^2(z) = w_0^2 + \theta^2 z^2 = w_0^2 + \theta^2(h + x\tan\alpha)^2. \qquad (6)$$

Transforming the coordinate system from the laser beam to the material surface can be expressed through the following equation:

$$x = X\cos\alpha,\ y = Y, \qquad (7)$$

where x and y are coordinates in the material surface reference frame. X and Y are coordinates in the laser beam reference frame.

Combining equations (6) and (7) into equation (5) leads to the derived equation:

$$q_2(X, Y) = q_{axis}\exp\left[-2\left(\frac{(X\cos\alpha)^2 + Y^2}{w_0^2 + \theta^2(h + X\sin\alpha)^2}\right)\right]. \qquad (8)$$

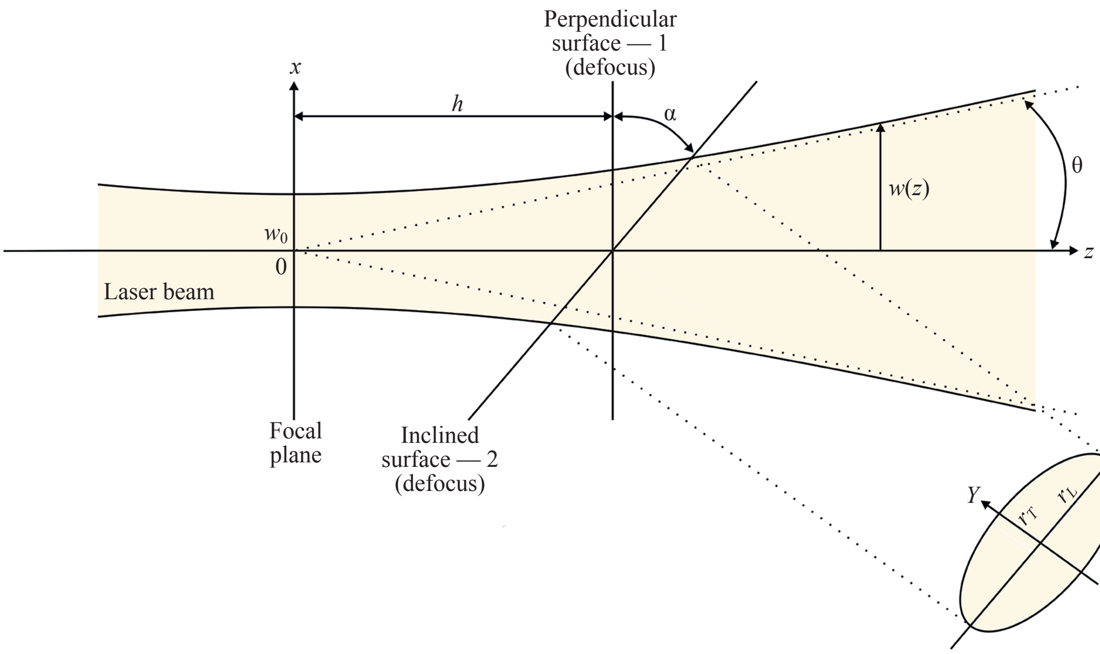

Fig. 4. Schematic of laser beam interaction on material surface; r_T is minor axis of ellipse; r_L is major axis of ellipse

Similar to equation (2), the total power of the laser beam can be computed using the following equation:

$$P\eta = \int_{-a_y}^{a_y}\int_{-a_y}^{a_x} \exp\left[-2\left(\frac{(X\cos\alpha)^2 + Y^2}{w_0^2 + \theta^2(h + X\sin\alpha)^2}\right)\right]dxdy. \quad (9)$$

For simplifying the calculation, new parameter D is introduced, as defined in the following equation:

$$D = \int_{-3r_T}^{3r_T}\int_{-3r_L}^{3r_L} \exp\left[-2\left(\frac{(X\cos\alpha)^2 + Y^2}{w_0^2 + \theta^2(h + X\sin\alpha)^2}\right)\right]dxdy, \quad (10)$$

where r_T and r_L are obtained according to the equations below:

$$r_T = \sqrt{w_0^2 + \theta^2 h^2 + \frac{(\theta^2 h\sin\alpha)^2}{\cos^2\alpha - \cos^2\sin^2\alpha}},$$

$$r_L = \sqrt{\frac{w_0^2 + \theta^2 + h^2}{\cos^2\alpha - \theta^2\sin^2\alpha} + \frac{(\theta^2 h\sin\alpha)^2}{(\cos^2\alpha - \theta^2\sin^2\alpha)^2}}.$$

By combining equation (8), (9), and (10), the heat source model equation can be calculated with the equation below:

$$q_2(X, Y) = \frac{P\eta}{D}\exp\left[-2\left(\frac{(X\cos\alpha)^2 + Y^2}{w_0^2 + \theta^2(h + X\sin\alpha)^2}\right)\right].$$

The mathematical model describing the laser beam spot on the material surface serves as a valuable tool for analyzing the characteristics of the laser beam spot. It facilitates the development of simulations to study variations in shape, size, and energy intensity of the laser beam spot on materials with uneven surfaces.

Development of Laser Beam Spot Simulation on Material Surface for Analyzing the Laser Beam Positioning Errors

This simulation is designed to investigate the impact of laser beam positioning errors on material or workpiece surfaces, particularly on those with irregularities. The underlying mathematical model serves as the foundation for the simulation development. Beyond assessing changes in the shape and size of the laser beam spot (defocus) due to positioning errors, this simulation also serves the crucial purpose of gauging the laser beam energy intensity and heat distribution is facilitated by employing a Partial Differential Equation (PDE), as denoted in the following equation within the computation domain:

$$\rho C\frac{\partial T}{\partial t} - \nabla(k\nabla T) = Q,$$

where ρ is the density, C is the heat capacity, T is the temperature, t is the time, k is the coefficient of heat conduction, ∇ is partial derivative operator, and Q is the heat source.

By combining the parameters of material properties and laser beam parameters, the simulation of surface heat treatment can be developed. The parameters are described in Table 1.

Table 1. Surface heat treatment parameters list

Constant	Value	Description
w_0, mm	1	Beam waist radius
θ, rad	0.033	Divergence half-angle
P, W	260	Laser power
C, J/(kg·K)	0.54	Heat capacity
k, J/(mm·K)	0.32	Coefficient of heat conduction
ρ, g/mm^3	0.078	Density

Moreover, leveraging these parameters enables the creation of simulation aimed at elucidating the impact of laser beam positioning errors on materials characterized by uneven surfaces. These simulations incorporate variables such as the incidence angle of the laser beam resulting from the inclined surface α and encompass the representation of the distance to the focal plane or laser beam focus h.

The simulation is executed using the PDE solver within the MATLAB software, employing the Finite Element method. This methodology ensures a swift and efficient solution to the surface heat treatment problem. The focus of this simulation is on surface heat treatment, aiming to ascertain the dimensions, shape, and the laser beam spot energy intensity or heat distribution on the material surface. Introducing the element of laser beam positioning error on uneven surfaces, the key variables under scrutiny are the incidence angle of the laser beam due to the inclined surface α and the representation of the distance to the focal plane or laser beam focus h. To enhance clarity, the conducted tests are detailed in Table 2.

Ten distinct conditions align with the variables α and h. The synthesis of parameters from Table 1 and incorporation of variables from Table 2 facilitate the development of a comprehensive simulation for surface heat treatment of the laser beam spot on materials with uneven surfaces. For more in-depth information about results in this simulation, refer to Fig. 5, 6, and 7.

The outcomes from the laser beam simulation conducted on the material surface underscore a significant impact of the material or workpiece surface on the shape and size of the laser beam spot. This alteration in the laser beams characteristics on the material surface is termed as the laser beam positioning error. The ongoing emphasis is

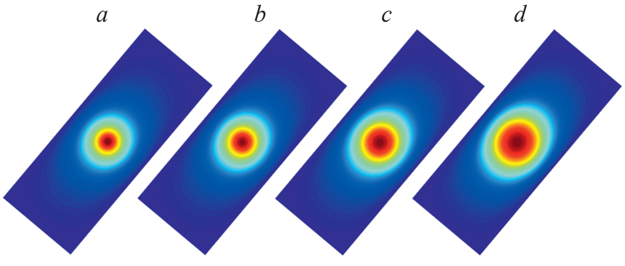

Fig. 5. Surface heat treatment of positive laser beam spot defocus on even/flat material surface with variable: $\alpha = 0$, $h = 0$ mm (*a*); $\alpha = 0$, $h = 25$ mm (*b*); $\alpha = 0$, $h = 50$ mm (*c*); $\alpha = 0$, $h = 75$ mm (*d*)

Table 2. Variables in surface heat treatment simulation

Conditions	Inclined surface α, rad	Distance to focus h, mm	Beam spot radius — 1 r_T, mm	Beam spot radius — 2 r_L, mm
1	0	0	1.000	1.000
2	0	25	1.296	1.296
3	0	50	1.929	1.929
4	0	75	2.669	2.669
5	0.436	0	1.000	1.104
6	0.873	0	1.000	1.557
7	1.309	0	1.000	3.893
8	0.436	25	1.296	1.431
9	0.873	50	1.930	3.006
10	1.309	75	2.687	10.461

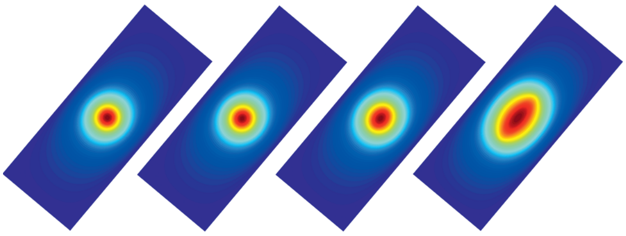

Fig. 6. Surface heat treatment of laser beam spot on inclined or uneven material surface with variable: $\alpha = 0$, $h = 0$ mm (*a*); $\alpha = 0.436$ rad, $h = 0$ mm (*b*); $\alpha = 0.873$ rad, $h = 0$ mm (*c*); $\alpha = 1.309$ rad, $h = 0$ mm (*d*)

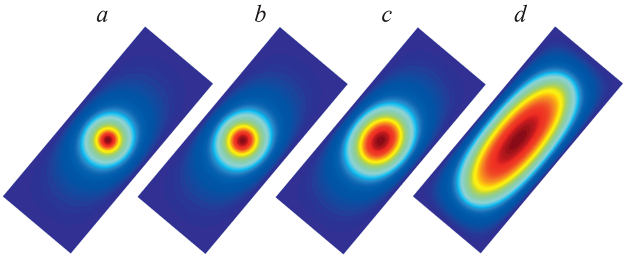

Fig. 7. Surface heat treatment of positive laser beam spot defocus on inclined or uneven material surface with variable: $\alpha = 0$, $h = 0$ mm (*a*); $\alpha = 0.436$ rad, $h = 25$ mm (*b*); $\alpha = 0.873$ rad, $h = 50$ mm (*c*); $\alpha = 1.309$ rad, $h = 75$ mm (*d*)

placed on delving deeper into this laser beam positioning error, with the ultimate goal of compensating or eliminating this discrepancy through further study and analysis.

Analysis of Simulation Result of Incidence Angle and Focal Plane Distance of Laser Beam on Material Surface

The exploration of laser beam spot characteristics through surface heat treatment simulations is geared towards understanding the impact of material surface processing on the laser beam spot size and shape. In developing the simulation, two pivotal variables, namely, the incidence angle of the laser beam α and the distance from the focus beam or beam waist to the material surface h — contribute to the creation of 10 distinct conditions meticulously outlined in Table 2.

Condition 1 serves as a reference, situating the laser beam spot precisely at the beam waist or focus beam on the material surface, with $\alpha = 0$ rad and $h = 0$ mm. This baseline condition facilitates a comparative analysis, enabling a clearer evaluation of changes in size and shape across other laser beam spots.

Conditions 2 to 4 involve scenarios where the laser beam position is perpendicular to the material surface, yet the focus beam or beam waist is positioned above, creating a positive defocus situation. Positive defocus leads to an enlarged laser beam spot, with the size increasing proportionally to the distance between the beam waist and the material surface as depicted in Fig. 5 and Fig. 8 above.

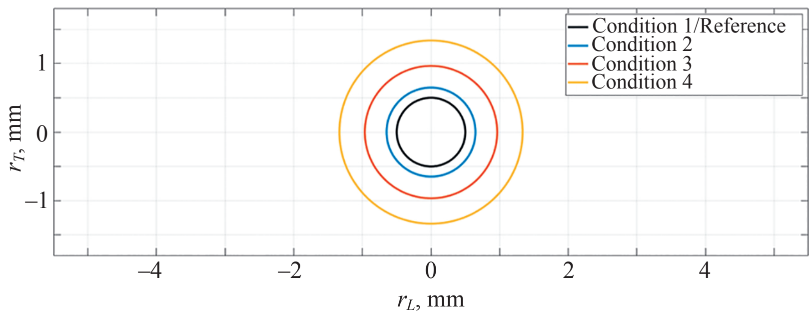

Fig. 8. Comparison of changes in the shape and size of the laser beam spot based on conditions 2 to 4

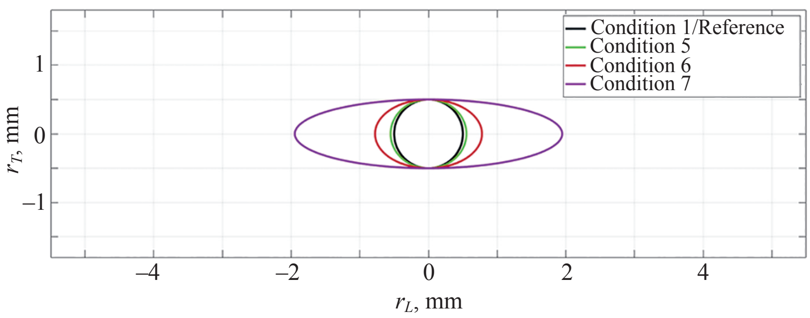

Fig. 9. Comparison of changes in the shape and size of the laser beam spot based on conditions 5 to 7

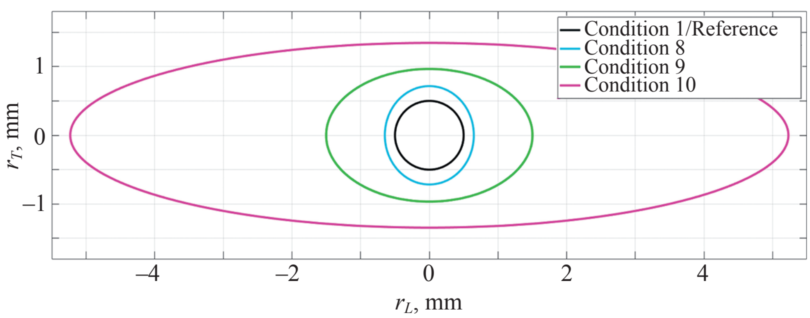

Fig. 10. Comparison of changes in the shape and size of the laser beam spot based on conditions 8 to 10

For conditions 2 to 4, this distance is set at 25, 50, and 75 mm, respectively.

Moving to conditions 5 through 7, the laser beam position on the material surface becomes uneven or inclined. This inclination induces an angle altering the beam perpendicularity to the material surface, consequently changing the shape of the laser beam spot. As illustrated in Fig. 6 and 9 above, the shape transforms into an ellipse with increasing inclination angles set at 0.436, 0.873, and 1.309 rad for conditions 5 to 7.

Conditions 8 to 10 represent a combination of conditions 2 to 7, introducing positive defocus and an uneven or inclined material surface. This amalgamation results in size and shape variations compared to condition 1, with the laser beam spot enlarging and adopting a more ellipse shape as the distance and inclination angle increase. In these conditions, the distance from the beam waist or focus beam to the material surface is set at 25, 50, and 75 mm, while the inclination angles are 0.436, 0.873, and 1.309 rad, respectively, as depicted in Fig. 7 and Fig. 10 above.

Conclusion

This research endeavors to address and rectify laser beam position errors during surface processing of materials. The specific error involves the laser beam not being perpendicular to the workpiece surface, coupled with the beam waist or focus beam not aligning precisely with the surface. Uneven workpiece or material surfaces contribute to this discrepancy, inducing changes in the laser beam spot shape and size. These alterations negatively impact the quality of laser processing outcomes. To combat such laser position errors, this research introduces a method aimed at endowing the laser beam with adaptability to various workpiece surfaces, ensuring a constant perpendicular orientation and maintaining beam waist stability on the surface.

The proposed method is currently in the developmental phase, progressing through distinct stages to optimize its efficacy. In the ongoing research stage, a simulation has been devised to identify and validate the characteristics of laser beam positioning errors on material surfaces. Simulation results affirm that deviations in the laser beam spot shape and size are directly influenced by the non-perpendicular alignment of the laser to the workpiece surface and the defocused beam waist or focus. Additionally, it was observed that an increased distance between the focus beam or beam waist and the material surface correlates with a larger laser beam spot. Moreover, greater inclination angles introduced by the laser beam against the workpiece surface lead to an increasingly ellipse-shaped laser beam spot.

Subsequently, the data gleaned from the simulation serves as a foundational reference for real-world testing and comparison with experimental data. This empirical validation aims to enhance our understanding of laser beam position errors on material surfaces and serve as a pivotal point for the ongoing development of methods designed to detect and identify such errors in laser beam spots.

References

1. Leniart A.A., Pula P., Sitkiewicz A., Majewski P.W. Macroscopic alignment of block copolymers on silicon substrates by laser annealing. *ACS Nano*, 2020, vol. 14, no. 4, pp. 4805–4815. https://doi.org/10.1021/acsnano.0c00696
2. Téllez H., Vadillo J.M., Chater R.J., Laserna J.J., McPhail D.S. Focused ion beam imaging of laser ablation sub-surface effects on layered materials. *Applied Surface Science*, 2008, vol. 255, no. 5, part 1, pp. 2265–2269. https://doi.org/10.1016/J.APSUSC.2008.07.082
3. Shaheen M.E., Gagnon J.E., Fryer B.J. Studies on laser ablation of silicon using near IR picosecond and deep UV nanosecond lasers. *Optics and Lasers Engineering*, 2019, vol. 119, pp. 18–25. https://doi.org/10.1016/j.optlaseng.2019.02.003
4. Žemaitis A., Gaidys M., Brikas M., Gečys P., Račiukaitis G., Gedvilas M. Advanced laser scanning for highly-efficient ablation and ultrafast surface structuring: experiment and model. *Scientific Reports*, 2018, vol. 8, pp. 17376. https://doi.org/10.1038/s41598-018-35604-z
5. Sobotova L., Badida M. Laser marking as environment technology. *Open Engineering*, 2017, vol. 7, no. 1, pp. 303–316. https://doi.org/10.1515/eng-2017-0030
6. Indrišiūnas S., Gedvilas M. Control of the wetting properties of stainless steel by ultrashort laser texturing using multi-parallel beam processing. *Optics & Laser Technology*, 2022, vol. 153, pp. 108187. https://doi.org/10.1016/j.optlastec.2022.108187
7. Obilor A.F., Pacella M., Wilson A., Silberschmidt V.V. Micro-texturing of polymer surfaces using lasers: a review. *The International Journal of Advanced Manufacturing Technology*, 2022, vol. 120, no. 1-2, pp. 103–135. https://doi.org/10.1007/s00170-022-08731-1
8. Sugar P., Sugarova J., Frncik M. Laser surface texturing of tool steel: textured surfaces quality evaluation. *Open Engineering*, 2016, vol. 6, no. 1, pp. 90–97. https://doi.org/10.1515/eng-2016-0012
9. Mao B., Siddaiah A., Liao Y., Menezes P.L. Laser surface texturing and related techniques for enhancing tribological performance of engineering materials: a review. *Journal of Manufacturing Processes*, 2020, vol. 53, pp. 153–173. https://doi.org/10.1016/j.jmapro.2020.02.009
10. Yang Y., Zhao Y., Wang L., Zhao Y. Application of femtosecond laser etching in the fabrication of bulk SiC accelerometer. *Journal of Materials Research and Technology*, 2022, vol. 17, pp. 2577–2586. https://doi.org/10.1016/j.jmrt.2022.02.012
11. Ehrhardt M., Lorenz P., Bauer J., Heinke R., Hossain M.A., Han B., Zimmer K. Dry etching of germanium with laser induced reactive micro plasma. *Lasers in Manufacturing and Materials Processing*, 2021, vol. 8, no. 3, pp. 237–255. https://doi.org/10.1007/s40516-021-00147-1
12. Mulko L., Soldera M., Lasagni A.F. Structuring and functionalization of non-metallic materials using direct laser interference patterning: a review. *Nanophotonics*, 2022, vol. 11, no. 2, pp. 203–240. https://doi.org/10.1515/nanoph-2021-0591
13. Krishnan A., Fang F. Review on mechanism and process of surface polishing using lasers. *Frontiers of Mechanical Engineering*, 2019, vol. 14, no. 3, pp. 299–319. https://doi.org/10.1007/s11465-019-0535-0
14. Xiao H., Chen Y., Liu M., Zhou Y., Du C., Zhang W. Influence of laser additive manufacturing and laser polishing on microstructures and mechanical properties of high-strength maraging steel metal materials. *Applied Sciences*, 2022, vol. 12, no. 20, pp. 10340. https://doi.org/10.3390/app122010340
15. Rizki M.A., Fedosov Yu.V. Development of adaptive laser head for compensating error of beam waist position during processing materials using laser beam spot detection method. *Scientific and Technical Journal of Information Technologies, Mechanics and Optics*, 2023, vol. 23, no. 5, pp. 859–870. https://doi.org/10.17586/2226-1494-2023-23-5-859-870
16. Evdokimov A., Jasiewicz F., Doynov N., Ossenbrink R., Michailov V. Simulation of surface heat treatment with inclined laser beam. *Journal of Manufacturing Processes*, 2022, vol. 81, pp. 107–114. https://doi.org/10.1016/j.jmapro.2022.06.051
17. Dai K., Shaw L. Distortion minimization of laser-processed components through control of laser scanning patterns. *Rapid Prototyping Journal*, 2002, vol. 8, no. 5, pp. 270–276. https://doi.org/10.1108/13552540210451732

Литература

1. Leniart A.A., Pula P., Sitkiewicz A., Majewski P.W. Macroscopic alignment of block copolymers on silicon substrates by laser annealing // ACS Nano. 2020. V. 14. N 4. P. 4805–4815. https://doi.org/10.1021/acsnano.0c00696
2. Téllez H., Vadillo J.M., Chater R.J., Laserna J.J., McPhail D.S. Focused ion beam imaging of laser ablation sub-surface effects on layered materials // Applied Surface Science. 2008. V. 255. N 5. Part 1. P. 2265–2269. https://doi.org/10.1016/J.APSUSC.2008.07.082
3. Shaheen M.E., Gagnon J.E., Fryer B.J. Studies on laser ablation of silicon using near IR picosecond and deep UV nanosecond lasers // Optics and Lasers Engineering. 2019. V. 119. P. 18–25. https://doi.org/10.1016/j.optlaseng.2019.02.003
4. Žemaitis A., Gaidys M., Brikas M., Gečys P., Račiukaitis G., Gedvilas M. Advanced laser scanning for highly-efficient ablation and ultrafast surface structuring: experiment and model // Scientific Reports. 2018. V. 8. P. 17376. https://doi.org/10.1038/s41598-018-35604-z
5. Sobotova L., Badida M. Laser marking as environment technology // Open Engineering. 2017. V. 7. N 1. P. 303–316. https://doi.org/10.1515/eng-2017-0030
6. Indrišiūnas S., Gedvilas M. Control of the wetting properties of stainless steel by ultrashort laser texturing using multi-parallel beam processing // Optics & Laser Technology. 2022. V. 153. P. 108187. https://doi.org/10.1016/j.optlastec.2022.108187
7. Obilor A.F., Pacella M., Wilson A., Silberschmidt V.V. Micro-texturing of polymer surfaces using lasers: a review // The International Journal of Advanced Manufacturing Technology. 2022. V. 120. N 1-2. P. 103–135. https://doi.org/10.1007/s00170-022-08731-1
8. Sugar P., Sugarova J., Frncik M. Laser surface texturing of tool steel: textured surfaces quality evaluation // Open Engineering. 2016. V. 6. N 1. P. 90–97. https://doi.org/10.1515/eng-2016-0012
9. Mao B., Siddaiah A., Liao Y., Menezes P.L. Laser surface texturing and related techniques for enhancing tribological performance of engineering materials: a review // Journal of Manufacturing Processes. 2020. V. 53. P. 153–173. https://doi.org/10.1016/j.jmapro.2020.02.009
10. Yang Y., Zhao Y., Wang L., Zhao Y. Application of femtosecond laser etching in the fabrication of bulk SiC accelerometer // Journal of Materials Research and Technology. 2022. V. 17. P. 2577–2586. https://doi.org/10.1016/j.jmrt.2022.02.012
11. Ehrhardt M., Lorenz P., Bauer J., Heinke R., Hossain M.A., Han B., Zimmer K. Dry etching of germanium with laser induced reactive micro plasma // Lasers in Manufacturing and Materials Processing. 2021. V. 8. N 3. P. 237–255. https://doi.org/10.1007/s40516-021-00147-1
12. Mulko L., Soldera M., Lasagni A.F. Structuring and functionalization of non-metallic materials using direct laser interference patterning: a review // Nanophotonics. 2022. V. 11. N 2. P. 203–240. https://doi.org/10.1515/nanoph-2021-0591
13. Krishnan A., Fang F. Review on mechanism and process of surface polishing using lasers // Frontiers of Mechanical Engineering. 2019. V. 14. N 3. P. 299–319. https://doi.org/10.1007/s11465-019-0535-0
14. Xiao H., Chen Y., Liu M., Zhou Y., Du C., Zhang W. Influence of laser additive manufacturing and laser polishing on microstructures and mechanical properties of high-strength maraging steel metal materials // Applied Sciences. 2022. V. 12. N 20. P. 10340. https://doi.org/10.3390/app122010340
15. Rizki M.A., Fedosov Yu.V. Development of adaptive laser head for compensating error of beam waist position during processing materials using laser beam spot detection method // Scientific and Technical Journal of Information Technologies, Mechanics and Optics. 2023. V. 23. N 5. P. 859–870. https://doi.org/10.17586/2226-1494-2023-23-5-859-870
16. Evdokimov A., Jasiewicz F., Doynov N., Ossenbrink R., Michailov V. Simulation of surface heat treatment with inclined laser beam // Journal of Manufacturing Processes. 2022. V. 81. P. 107–114. https://doi.org/10.1016/j.jmapro.2022.06.051
17. Dai K., Shaw L. Distortion minimization of laser-processed components through control of laser scanning patterns // Rapid Prototyping Journal. 2002. V. 8. N 5. P. 270–276. https://doi.org/10.1108/13552540210451732
18. Messaoudi H., Thiemicke F., Falldorf C., Bergmann R.B., Vollertsen F. Distortion-free laser beam shaping for material processing using a

18. Messaoudi H., Thiemicke F., Falldorf C., Bergmann R.B., Vollertsen F. Distortion-free laser beam shaping for material processing using a digital micromirror device. *Production Engineering*, 2017, vol. 11, no. 3, pp. 365–371. https://doi.org/10.1007/s11740-017-0722-y
19. Moraitis G.A., Labeas G.N. Residual stress and distortion calculation of laser beam welding for aluminum lap joints. *Journal of Materials Processing Technology*, 2008, vol. 198, no. 1-3, pp. 260–269. https://doi.org/10.1016/j.jmatprotec.2007.07.013
20. Zahrani E.G., Marasi A. Experimental investigation of edge effect and longitudinal distortion in laser bending process. *Optics and Laser Technology*, 2013, vol. 45, no. 1. pp. 301–307. https://doi.org/10.1016/j.optlastec.2012.06.031
21. Safdar S., Li N., Sheikh M.A., Liu Z. The effect of nonconventional laser beam geometries on stress distribution and distortions in laser bending of tubes. *Journal of Manufacturing Science and Engineering*, 2007, vol. 129, no. 3, pp. 592–600. https://doi.org/10.1115/1.2716715
22. Galaktionov I., Sheldakova J., Nikitin A., Toporovsky V., Kudryashov A. A hybrid model for analysis of laser beam distortions using monte carlo and Shack–Hartmann techniques: numerical study and experimental results. *Algorithms*, 2023, vol. 16, no. 7, pp. 337. https://doi.org/10.3390/a16070337
23. Marom D.M. Optical communications. *Comprehensive Microsystems*, 2007, vol. 3, pp. 219–265. https://doi.org/10.1016/B978-044452190-3.00035-5
24. Paschotta R. Laser Beams. *RP Photonics Encyclopedia*, 2005, https://doi.org/10.61835/ggt

digital micromirror device // Production Engineering. 2017. V. 11. N 3. P. 365–371. https://doi.org/10.1007/s11740-017-0722-y
19. Moraitis G.A., Labeas G.N. Residual stress and distortion calculation of laser beam welding for aluminum lap joints // Journal of Materials Processing Technology. 2008. V. 198. N 1-3. P. 260–269. https://doi.org/10.1016/j.jmatprotec.2007.07.013
20. Zahrani E.G., Marasi A. Experimental investigation of edge effect and longitudinal distortion in laser bending process // Optics and Laser Technology. 2013. V. 45. N 1. P. 301–307. https://doi.org/10.1016/j.optlastec.2012.06.031
21. Safdar S., Li N., Sheikh M.A., Liu Z. The effect of nonconventional laser beam geometries on stress distribution and distortions in laser bending of tubes // Journal of Manufacturing Science and Engineering. 2007. V. 129. N 3. P. 592–600. https://doi.org/10.1115/1.2716715
22. Galaktionov I., Sheldakova J., Nikitin A., Toporovsky V., Kudryashov A. A hybrid model for analysis of laser beam distortions using monte carlo and Shack–Hartmann techniques: numerical study and experimental results // Algorithms. 2023. V. 16. N 7. P. 337. https://doi.org/10.3390/a16070337
23. Marom D.M. Optical communications // Comprehensive Microsystems. 2007. V. 3. P. 219–265. https://doi.org/10.1016/B978-044452190-3.00035-5
24. Paschotta R. Laser Beams // RP Photonics Encyclopedia. 2005. https://doi.org/10.61835/ggt

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