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DESIGN OF AN ADDITIVE MANUFACTURING SYSTEM FOR PRODUCING DEFENSE-ORIENTED METAL COMPONENTS

Abstract. This study presents a conceptual design and analysis of an additive manufacturing system based on the Selective Laser Melting (SLM) process, with a focus on the optimization of process parameters and thermal behavior. The research addresses the critical challenge of achieving stable melting conditions, minimizing defect formation, and ensuring high mechanical performance of fabricated components. An integrated framework combining system architecture, process parameter analysis, and thermal modeling is proposed. The influence of scanning speed and energy density on mechanical properties, porosity, melt pool characteristics, and residual stress is investigated. The results demonstrate that optimal process conditions, particularly within a scanning speed range of 600-800 mm/s and energy density of 60-90 J/mm³, provide a balanced combination of strength, ductility, and structural integrity. Thermal field analysis reveals the presence of localized heating, steep temperature gradients, and heat accumulation effects, which significantly influence microstructure formation and process stability. The findings confirm that controlled energy input and optimized thermal conditions are essential for reducing defects and improving the quality of SLM-produced components. The proposed approach is particularly relevant for the production of defense-oriented metallic components requiring high reliability and structural integrity. The study provides a theoretical basis for further experimental validation and practical implementation in advanced manufacturing systems.

Keywords: Selective Laser Melting, additive manufacturing, energy density, thermal modeling, porosity, defense-oriented components, optimization.

Introduction.

Additive manufacturing technologies have become one of the key directions in the development of modern engineering and high-tech production systems. Unlike traditional subtractive methods, additive manufacturing enables the creation of complex geometries directly from digital models, significantly reducing material waste and increasing production efficiency. This is particularly important in industries where high precision, structural complexity, and material performance are critical.

Among the various additive technologies, selective laser melting (SLM) occupies a special place due to its ability to produce dense metallic components with high mechanical properties. The process is based on the layer-by-layer melting of metal powder using a high-energy laser beam, allowing the fabrication of parts with complex internal structures and optimized geometries. These capabilities make SLM especially relevant for defense and aerospace applications, where components must meet strict requirements in terms of strength, reliability, and operational performance.

However, the stability and quality of the SLM process depend on a complex interaction of process parameters, including laser power, scanning speed, layer thickness, and hatch spacing. Improper parameter selection leads to defects such as porosity, incomplete fusion, and residual stresses, which significantly affect the performance of manufactured components. In this context, the problem of designing an efficient additive manufacturing system with optimized process parameters becomes highly relevant.

The novelty of this study lies in the integrated approach to the design of an additive manufacturing system, combining structural configuration, process parameter optimization, and thermal modeling. Unlike existing approaches that focus on individual aspects of the process, this work proposes a unified framework that considers both the physical behavior of the SLM process and the engineering design of the system.

In modern military-industrial systems, additive manufacturing technologies are becoming a key element in ensuring technological independence, operational flexibility, and rapid response capabilities. The ability to produce critical metal components directly at or near deployment zones significantly reduces logistical constraints and increases the survivability of technical systems under combat conditions. In particular, Selective Laser Melting (SLM) enables the fabrication of structurally complex and high-strength elements used in armored systems, aerospace platforms, and weapon subsystems. Under such conditions, the stability of the manufacturing process and the minimization of defects become critically important, as they directly affect the reliability and safety of defense equipment. Therefore, the development of optimized SLM-based manufacturing systems represents a strategically important task for modern defense engineering.

The aim of this study is to develop a conceptual design of an additive manufacturing system based on the SLM process and to determine optimal process parameters ensuring stable melting, minimal porosity, and high mechanical performance. The object of the study is the selective laser melting process of metallic powders and the associated thermal and mechanical phenomena.

It is hypothesized that the optimization of energy density and thermal conditions within a defined parameter range will lead to improved structural integrity and reduced defect formation in the manufactured components.

The structure of the paper is organized as follows: Section 2 presents a review of related works, Section 3 describes the materials and methods, Section 4 discusses the obtained results, and the final section summarizes the main findings.

Literature Review.

The study of selective laser melting processes has attracted significant attention in recent years, particularly in relation to process parameter optimization and defect control. A number of researchers have demonstrated that laser power and scanning speed are the dominant factors influencing energy input and melt pool stability [1].

It has been reported that insufficient energy density leads to lack-of-fusion defects, while excessive energy input results in keyhole formation and material evaporation, both of which negatively affect part quality [2]-[3]. Therefore, the identification of an optimal energy density range is considered a fundamental requirement for achieving high-density structures [4].

Thermal modeling plays a crucial role in understanding the physical mechanisms of the SLM process. Numerical approaches based on the heat conduction equation have been widely applied to predict temperature distribution and melt pool geometry [5]. These models enable the analysis of heat transfer and provide insight into the influence of process parameters on thermal behavior [6].

Several studies have also focused on the evolution of the temperature field during laser exposure. It has been shown that localized heating leads to steep thermal gradients, which are responsible for the development of residual stresses and microstructural heterogeneity [7]-[8]. These effects are particularly important in multi-layer fabrication, where heat accumulation can significantly influence process stability.

The relationship between thermal history and mechanical properties has been extensively investigated. It is well established that cooling rates and thermal gradients directly affect grain structure and phase transformations, which in turn determine strength and ductility [9]-[10].

At the same time, defect formation remains a major challenge in SLM processes. Porosity, cracking, and incomplete fusion significantly reduce mechanical performance and reliability [11]. Various strategies have been proposed to minimize these defects, including optimization of process parameters and control of energy input [12].

The geometry of the melt pool has also been identified as a key factor influencing layer bonding and structural integrity. Studies have shown that melt pool depth and width are directly related to energy density and scanning conditions [13].

Recent research emphasizes the importance of integrating thermal and mechanical modeling approaches. Combined models allow simultaneous evaluation of temperature distribution, stress development, and microstructure evolution, providing a more comprehensive understanding of the process.

Despite the significant progress in the study of selective laser melting processes, most existing works primarily focus on isolated aspects such as process parameter optimization, thermal modeling, or defect analysis. Limited attention has been given to the integration of these components within a unified framework that simultaneously considers system design, thermal behavior, and mechanical performance. In addition, the issue of process stability under varying operational conditions, which is particularly important for defense-oriented manufacturing systems, remains insufficiently addressed. Therefore, there is a clear need for comprehensive approaches that combine parameter optimization with thermal and structural analysis to ensure reliable and high-quality production of critical metallic components. The present study aims to address this gap by proposing an integrated modeling and design framework for the SLM process.

Materials and Methods.

Selective Laser Melting (SLM) is an advanced additive manufacturing technique based on the layer-by-layer consolidation of metallic powders using a high-energy laser beam. In the present study, the SLM process is considered as a complex thermo-physical system that integrates powder deposition, localized melting, heat transfer, and solidification phenomena.

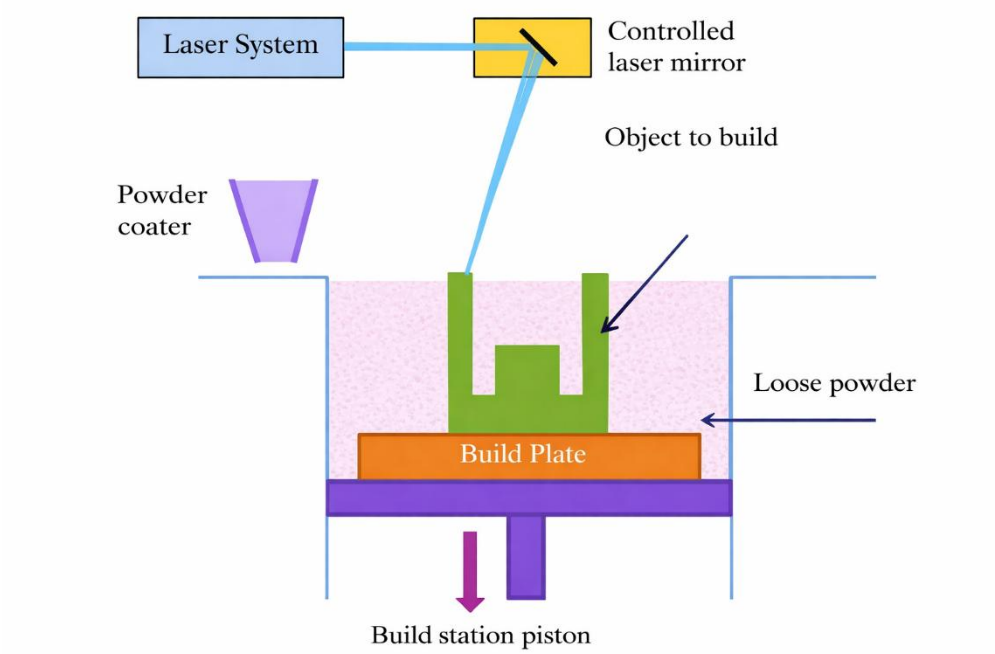

Figure 1 - SLM process and system architecture

The overall architecture and working principle of the SLM system are presented in Figure 1. The system consists of a high-power fiber laser, a galvanometer-based scanning system, a recoating mechanism for powder distribution, and a vertically controlled build platform. During fabrication, a thin layer of metal powder is uniformly spread across the build area, after which the laser selectively scans the surface according to the predefined geometry. The laser-material interaction results in localized melting of the powder, followed by rapid solidification as the heat dissipates into the surrounding material.

Subsequently, the build platform is lowered by one layer thickness, and the process is repeated. This cyclic operation enables the fabrication of complex three-dimensional structures while simultaneously generating significant thermal gradients that influence the microstructure and mechanical properties of the manufactured component.

To investigate the thermal behavior of the SLM process, a conceptual modeling approach was employed to represent the evolution of the thermal field and the distribution of energy during laser exposure. The developed model captures the key stages of the process, including the initial powder state, the melting phase characterized by a rapid increase in temperature, and the subsequent solidification phase during which the material cools and stabilizes.

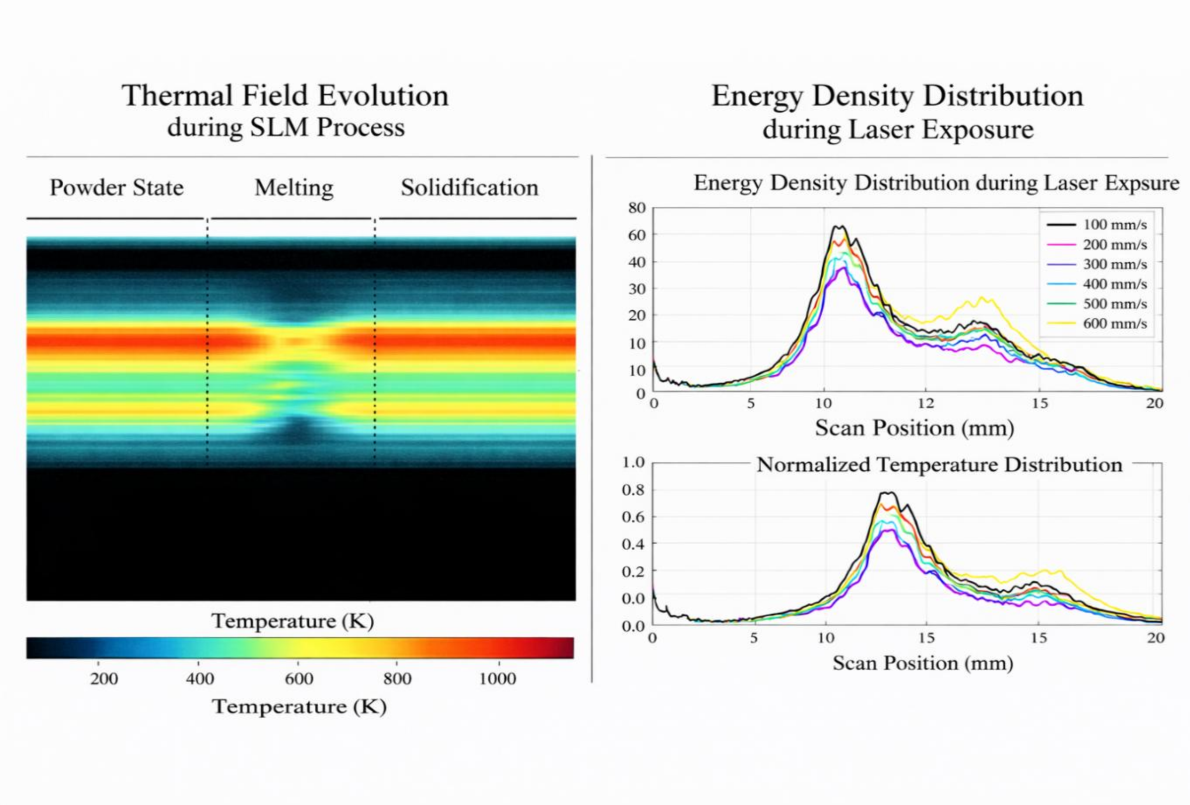

Figure 2 - Thermal field and energy density in the SLM process

The schematic representation of the thermal field evolution and energy density distribution is illustrated in Figure 2. The thermal field is described as a spatial temperature distribution resulting from the interaction between the moving laser heat source and the powder bed. The localized energy input leads to the formation of a melt pool, with heat propagating both within the current layer and into previously solidified material.

The model emphasizes the dynamic nature of heat transfer in the SLM process, where temperature gradients continuously evolve as a function of laser movement and process parameters. This representation provides a qualitative understanding of the thermal mechanisms governing the additive manufacturing process.

The thermal behavior of the SLM process is strongly influenced by process parameters, particularly laser power and scanning speed. In this study, the effect of scanning speed on energy input and temperature distribution is considered within the developed modeling framework.

The energy density distribution along the scanning direction is represented as a function of spatial position, reflecting variations in heat input under different operating conditions. As shown in Figure 2, multiple curves correspond to different scanning speeds, demonstrating how variations in process parameters alter the shape and magnitude of the thermal response.

To enable a consistent comparison of thermal behavior, normalized temperature distributions are introduced. This approach allows the analysis of relative changes in temperature profiles, facilitating the identification of peak thermal regions, gradients, and cooling behavior independent of absolute temperature values.

In order to simplify the analysis and focus on the dominant physical mechanisms, several assumptions were adopted in the modeling framework. The powder bed was considered homogeneous and isotropic, and heat transfer was assumed to be primarily governed by conduction. The laser was modeled as a moving localized heat source, and phase transitions were treated within a simplified temperature range without explicitly modeling microstructural evolution.

To ensure the applicability of the proposed approach in defense-oriented manufacturing environments, a parametric optimization method was employed, focusing on the identification of stable and reliable process conditions under varying operational scenarios. The method involves systematic variation of key parameters, such as scanning speed and energy density, followed by the evaluation of their influence on thermal stability, melt pool behavior, and defect formation. Particular attention is given to process robustness, as fluctuations in manufacturing conditions are typical for decentralized or field-based production systems. This approach enables the determination of parameter ranges that ensure consistent material performance, reduced defect sensitivity, and enhanced structural reliability of critical components.

These assumptions enable the construction of a generalized and computationally efficient representation of the thermal behavior in the SLM process, which is sufficient for analyzing the influence of process parameters on energy distribution and temperature evolution.

Results and Discussion.

The mechanical response of the fabricated samples under varying scanning speeds is presented in Figure 3. The stress-strain behavior demonstrates a typical elastoplastic response, characterized by an initial linear region followed by strain hardening and gradual softening.

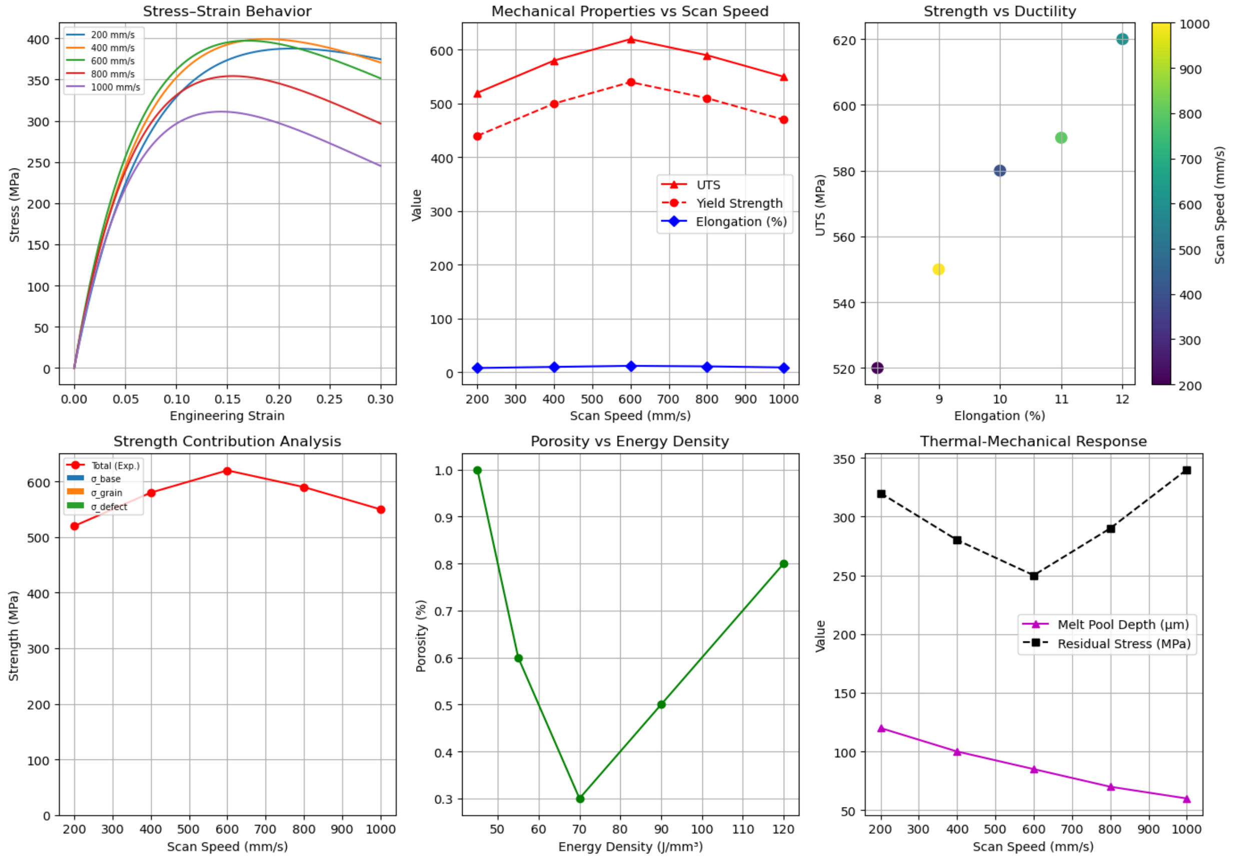

Figure 3 - Effect of scanning speed on mechanical and process properties

It is observed that the mechanical properties strongly depend on the scanning speed in Figure 3. At intermediate values (approximately 600-800 mm/s), the material exhibits the highest ultimate tensile strength, reaching up to 620 MPa. At lower scanning speeds, excessive energy input leads to overheating effects, while at higher speeds insufficient melting occurs, resulting in reduced mechanical performance. The relationship between strength and ductility presented in Figure 3 indicates that the optimal process window provides a balanced combination of high strength and sufficient elongation. Outside this region, either brittleness or structural defects dominate the material behavior.

A clear non-linear dependence is observed, where porosity decreases with increasing energy density up to an optimal range, after which it begins to increase again. At low energy density levels, incomplete melting leads to lack-of-fusion defects. As the energy input increases, improved layer bonding reduces porosity. However, excessive energy input causes instability in the melt pool, including keyhole formation and material evaporation, which negatively affects structural integrity. These results confirm that maintaining a controlled energy density range is critical for achieving high-quality SLM components.

The thermal-mechanical behavior of the process is illustrated in Figure 3, where melt pool depth and residual stress are analyzed as functions of scanning speed. The melt pool depth decreases with increasing scanning speed due to reduced laser-material interaction time. At the same time, residual stresses exhibit

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a minimum in the optimal parameter range and increase toward both low and high scanning speeds due to thermal gradients. This behavior highlights the importance of balancing thermal input to avoid excessive stress accumulation and distortion.

The contribution of different strengthening mechanisms is also reflected in Figure 3. The results indicate that the overall strength is governed by a combination of base material properties, grain refinement, and defect-related effects. At optimal scanning speeds, grain refinement dominates, leading to enhanced strength. In contrast, deviations from optimal conditions increase the influence of defects, which reduces mechanical performance.

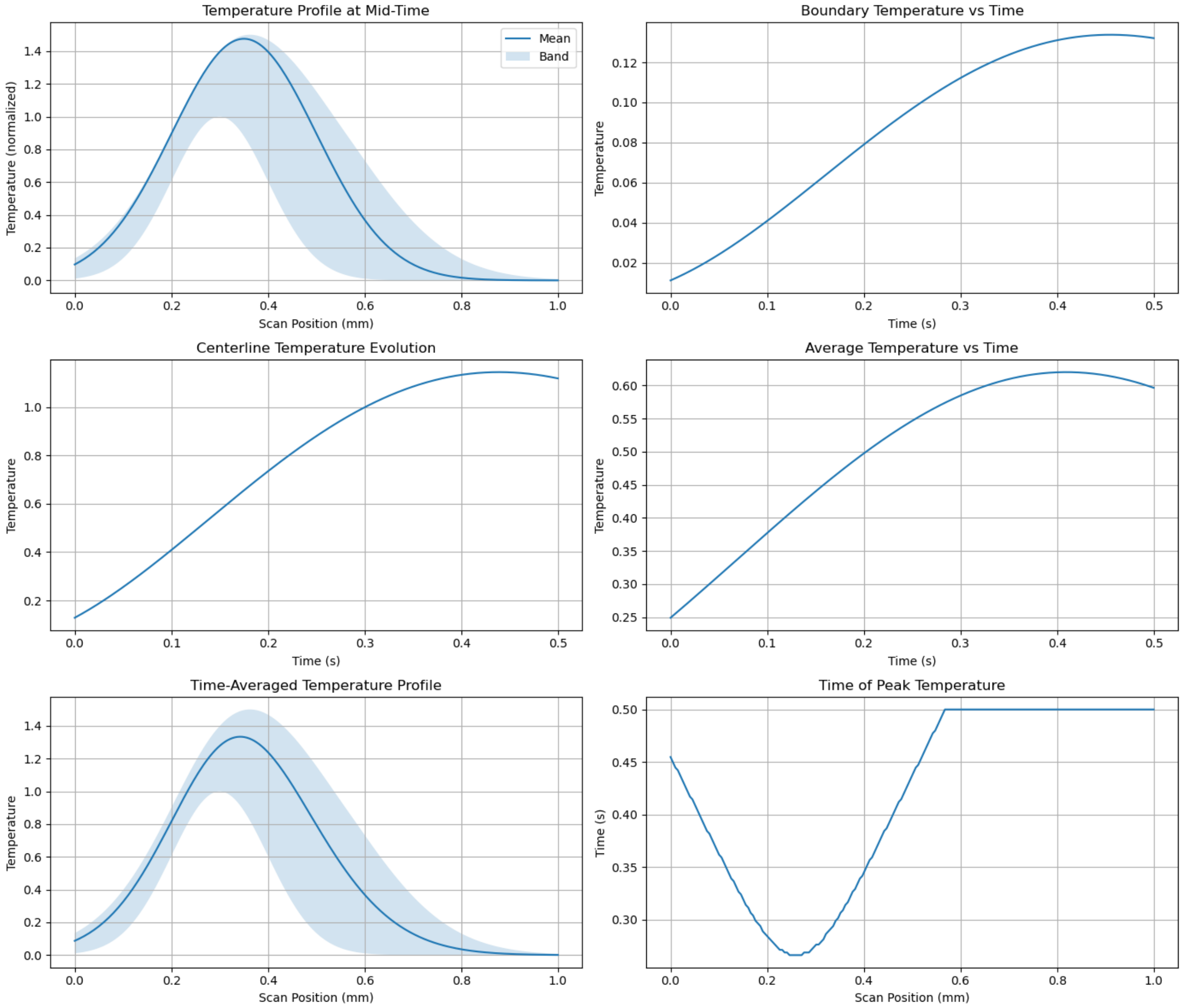

Figure 4 - Temperature field evolution during the SLM process

The evolution of the temperature field during the SLM process is presented in Figure 4. The results demonstrate the spatial and temporal dynamics of heat distribution during laser exposure. The temperature distribution exhibits a pronounced peak corresponding to the laser interaction zone, with gradual decay toward the surrounding regions. Over time, heat accumulation leads to an increase in average temperature, indicating the presence of thermal memory effects in the system. The temporal evolution shows that the maximum temperature is reached at intermediate stages of the process, after which stabilization occurs. The spatial distribution follows a Gaussian-like profile, typical for localized laser heating.

Overall, the results highlight the critical role of thermal behavior in determining process stability, microstructure formation, and final material properties.

Based on the obtained results, the optimal process parameters are summarized in Table 1.

Table 1 - Optimal SLM process parameters and corresponding characteristics

Parameter	Optimal Range	Effect on Process
Laser Power (W)	300-350	Stable melting
Scan Speed (mm/s)	600-800	Optimal mechanical properties
Energy Density (J/mm³)	60-90	Minimum porosity
Melt Pool Depth (μm)	80-100	Good layer bonding
Porosity (%)	< 0.5	High density
Residual Stress (MPa)	~250	Reduced deformation

The results summarized in Table 1 clearly demonstrate that the performance of the SLM process is highly sensitive to the selection of process parameters. The identified optimal ranges ensure a balanced combination of mechanical strength, structural integrity, and thermal stability.

In particular, the scanning speed plays a dominant role in controlling both the energy input and the resulting microstructural characteristics. Operating within the optimal range allows for sufficient melting and proper layer bonding, while minimizing defect formation and residual stress accumulation.

The obtained results are consistent with the thermal and mechanical trends observed in Figures 3 and 4, confirming the validity of the proposed modeling approach. The combination of mechanical analysis and thermal field evaluation provides a comprehensive understanding of the process behavior.

Overall, the findings highlight that the integration of process parameter optimization and thermal modeling is essential for achieving high-quality additive manufacturing of metallic components. These results form a reliable basis for further experimental validation and industrial implementation of the proposed SLM system.

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From a defense application perspective, the obtained results demonstrate the importance of maintaining stable process conditions to ensure the reliability of critical components operating under extreme conditions. The identified optimal parameter ranges provide a basis for manufacturing structurally sound elements with predictable mechanical performance and minimal defect levels. This is particularly relevant for components subjected to dynamic loads, thermal fluctuations, and mechanical stress in military systems. The ability to control energy input and thermal behavior contributes to improved durability, reduced failure probability, and enhanced operational safety. These findings confirm the potential of the proposed approach for implementation in advanced defense manufacturing systems, including mobile production units and rapid deployment scenarios.

Conclusion.

This study presents a conceptual design and analysis of an additive manufacturing system based on the Selective Laser Melting (SLM) process, with a focus on process parameter optimization and thermal behavior. The results demonstrate that the stability and quality of the SLM process are strongly dependent on the selection of key parameters, particularly scanning speed and energy density.

It has been established that the optimal scanning speed range of 600–800 mm/s and energy density of 60–90 J/mm³ обеспечивают a balanced combination of mechanical strength, reduced porosity, and stable melt pool formation. The analysis of thermal field evolution revealed the presence of localized heating, steep temperature gradients, and heat accumulation effects, which significantly influence microstructure formation and residual stress development.

The proposed integrated approach, combining system design, parameter optimization, and thermal modeling, allows for a comprehensive understanding of the SLM process and provides a basis for improving manufacturing efficiency and component quality.

From a practical perspective, the obtained results are relevant for defense-oriented manufacturing systems, where the reliability and durability of critical components are essential. The identified optimal parameter ranges can be used as guidelines for the production of high-performance metallic parts with reduced defect levels and improved operational characteristics.

Future work will be focused on experimental validation of the proposed model and the development of adaptive control strategies for real-time process optimization in advanced manufacturing systems.

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ҚОРҒАНЫС МЕТАЛЛ ӨНІМДЕРІНЕ АРНАЛҒАН ҚОСПА ӨНДІРУ ЖҮЙЕСІН ЖОБАЛАУ

Аңдатпа. Бұл зерттеуде селективті лазерлік балқыту (SLM) процесіне негізделген аддитивті өндіріс жүйесінің тұжырымдамалық дизайны мен талдауы ұсынылған, ол процесс параметрлері мен термиялық мінез-құлықты оңтайландыруға бағытталған. Зерттеу тұрақты балқу жағдайларына қол жеткізу, ақаулардың пайда болуын азайту және өндірілген компоненттердің жоғары механикалық қасиеттерін қамтамасыз ету сияқты маңызды міндеттерді шешеді. Жүйе архитектурасын, процесс параметрлерін талдауды және термиялық модельдеуді біріктіретін интеграцияланған құрылым ұсынылады. Сканерлеу жылдамдығы мен энергия тығыздығының механикалық қасиеттерге, кеуектілікке, балқытылған бассейн сипаттамаларына және қалдық кернеулерге әсері зерттелген. Нәтижелер оңтайлы процесс жағдайлары, әсіресе 600-800 мм/с сканерлеу жылдамдығы және 60-90 Дж/мм^3 энергия тығыздығы диапазонында беріктіктің, созылғыштықтың және құрылымдық тұтастықтың теңгерімді үйлесімін қамтамасыз ететінін көрсетеді. Жылу өрісін талдау микроқұрылымның пайда болуына және процестің тұрақтылығына айтарлықтай әсер ететін жергілікті қыздырудың, тік температура градиенттерінің және жылу жинақтау әсерлерінің бар екенін көрсетеді. Алынған нәтижелер жоғары сенімділік пен беріктік сипаттамаларын қажет ететін қорғаныс сапасындағы металл бұйымдарын өндіру үшін ерекше маңызды. Ұсынылған тәсіл қазіргі заманғы өндіріс жүйелерінде одан әрі эксперименттік тексеру және практикалық қолдану үшін теориялық негіз береді.

Түйінді сөздер: селективті лазерлік балқыту, аддитивті өндіріс, энергия тығыздығы, термиялық модельдеу, кеуектілік, қорғанысқа жарамды өнімдер, оңтайландыру.

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ПРОЕКТИРОВАНИЕ АДДИТИВНОЙ УСТАНОВКИ ДЛЯ ИЗГОТОВЛЕНИЯ МЕТАЛЛИЧЕСКИХ ИЗДЕЛИЙ ОБОРОННОГО НАЗНАЧЕНИЯ

Аннотация. В данном исследовании представлен концептуальный проект и анализ системы аддитивного производства, основанной на процессе селективного лазерного плавления (SLM), с акцентом на оптимизацию параметров процесса и теплового поведения. Исследование посвящено решению важнейшей задачи достижения стабильных условий плавления, минимизации образования дефектов и обеспечения высоких механических характеристик изготавливаемых компонентов. Предложена интегрированная структура, объединяющая архитектуру системы, анализ параметров процесса и тепловое моделирование. Исследовано влияние скорости сканирования и плотности энергии на механические свойства, пористость, характеристики расплавленной ванны и остаточные напряжения. Результаты показывают, что оптимальные условия процесса, особенно в диапазоне скоростей сканирования 600-800 мм/с и плотности энергии 60-90 Дж/мм^3, обеспечивают сбалансированное сочетание прочности, пластичности и структурной целостности. Анализ теплового поля выявляет наличие локального нагрева, крутых температурных градиентов и эффектов накопления тепла, которые существенно влияют на формирование микроструктуры и стабильность процесса. Полученные результаты имеют особую значимость для производства металлических изделий оборонного назначения, требующих высокой надежности и прочностных характеристик. Предложенный подход обеспечивает теоретическую основу для дальнейшей экспериментальной проверки и практического применения в современных производственных системах.

Ключевые слова: селективное лазерное плавление, аддитивное производство, плотность энергии, тепловое моделирование, пористость, изделия оборонного назначения, оптимизация.

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