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OPTIMIZING ENERGY EFFICIENCY AND PARAMETERS IN FUSED DEPOSITION MODELING ADDITIVE MANUFACTURING SYSTEMS: A MINI REVIEW

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Abstract: The widespread adoption of additive manufacturing (AM) is a noteworthy development in various spheres of everyday life. Numerous industries are embracing and incorporating this ground breaking technology. To meet the demands of customers and enhance production capabilities, companies are implementing advanced production technology in their field. This technology aims to boost production volumes, lower production costs, create intricate and lightweight components within tight timeframes, and effectively address customer manufacturing requirements. It is evident that these innovative technologies require energy for their operation. Understanding the effects of energy efficiency is crucial in order to grasp the production responsibilities associated with each component. This paper offers a comprehensive analysis of how to effectively and efficiently utilize these emerging technologies from an economic standpoint. The latest knowledge blocks on this crucial concept will be gathered and presented through a comprehensive examination that encompasses process, materials science, industry, and initiatives. The objective of this research study is to provide a review. The information regarding the energy usage of additive manufacturing (AM) technologies has been gathered from various up-to-date technical sources. These sources include surveys, observations, case studies, and other relevant content. The AM community is influenced by current trends and technologies related to energy efficiency, as revealed by various analyses, research studies, and archival research.

Keywords: Additive manufacturing, Energy efficiency, Process optimization, FDM.

I. Introduction:

AM, also referred to as one of the most recent industrial revolutions in the realm of manufacturing engineering [1]. Operates on a layer-by-layer construction method. This technology offers numerous benefits, including the ability to produce intricate, lightweight, and cost-effective work pieces. Essentially, AM is a game-changing advancement in the manufacturing industry. There are seven distinct categories within the realm of additive manufacturing, each employing unique materials and frameworks for constructing various components [2]. Despite their differences, all of these technologies share a common characteristic: the utilization of energy to execute the additive fabrication process. The field of additive manufacturing is constantly striving to enhance productivity across industries [3]. One of the primary solutions for industries looking to reduce production costs is to find ways to efficiently utilize energy. This involves identifying solutions and best practices that can help optimize energy utilization.

The research team has previously conducted studies to investigate the most suitable parameters for achieving this goal. They have discovered the optimal settings for 3D printing various components while minimizing energy usage. Their previous research yielded ground breaking results on the most efficient configurations, including layer height, infill ratio, and shell count. These findings are generally applicable to the field of 3D printing [4,5]. The authors of this review paper primarily utilize a methodology that involves gathering knowledge blocks from various archival research papers. These papers consist of surveys, observations, and experimentations, focusing on material extrusion and smart manufacturing technologies. Our research has utilized various methodologies, including case studies, and content analyses. To gather the most up-to-date trends, technologies, and information blocks related to our research topics, we have relied on databases such as Web of Science, Science Direct, and Google Scholar. Numerous studies have documented specific outcomes pertaining to the energy consumption of additive manufacturing.

The report focused on the analysis of AM, considering factors such as cost, process, technology, and trends. It also highlighted the various applications of AM in [6] industries such as nuclear energy, battery, fuel cell, oil, and gas. The scientific community acknowledges that metal additive manufacturing (MAM) holds great promise. In order to determine the optimal conditions for using AM and selecting the most suitable technology based on factors such as cost, energy efficiency, complexity, and material resources [7].

Energy conservation is of utmost significance, especially when it comes to energy-intensive materials like titanium. This holds particular importance in the aeronautic and aerospace industries. In their study on MAM, Monteiro [8] et al. examined strategies for energy and efficiency in different sectors. The aeronautic and aerospace industries have been highlighted, with a focus on the fact that conventional manufacturing sectors tend to produce significant amounts of waste while consuming energy and resources concurrently. To tackle the problem of excessive waste production, a group of scientists have pinpointed key phases in the life cycle where resource efficiency techniques utilizing MAM can be implemented [9]. These stages encompass various aspects such as product design specifications, material sourcing and development, process enhancement, control and optimization, extending the lifespan of products, and incorporating circular economy principles, as illustrated in Figure 1.

II. Additive Manufacturing Process:

The research paper outlines the latest research inquiries and significant findings within seven additive manufacturing (AM) processes. These processes are categorized based on ISO and ASTM [10] standards, as depicted in Figure 1.

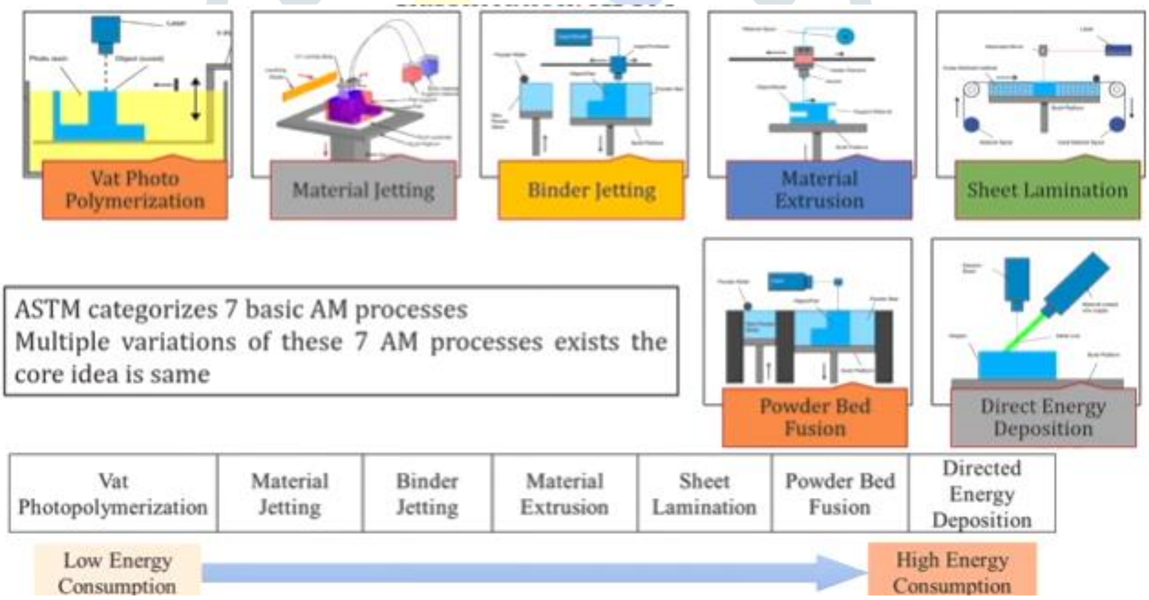

Figure 1. Classification of AM technologies.

II.I FDM Method:

Stratasys, a pioneer in additive manufacturing, introduced the Fused Deposition Modeling (FDM) technology in the early 90s. This method, also known as Fused Filament Fabrication (FFF) [11], enables the production of parts using thermoplastic materials. FDM/FFF has garnered immense interest due to its versatility and accessibility, allowing for the construction of custom devices based on Stratasys products. Illustrated in Figure 2, the operating principle of FDM involves the layer-by-layer deposition of material, making it the most widespread and accessible additive manufacturing technology available today.

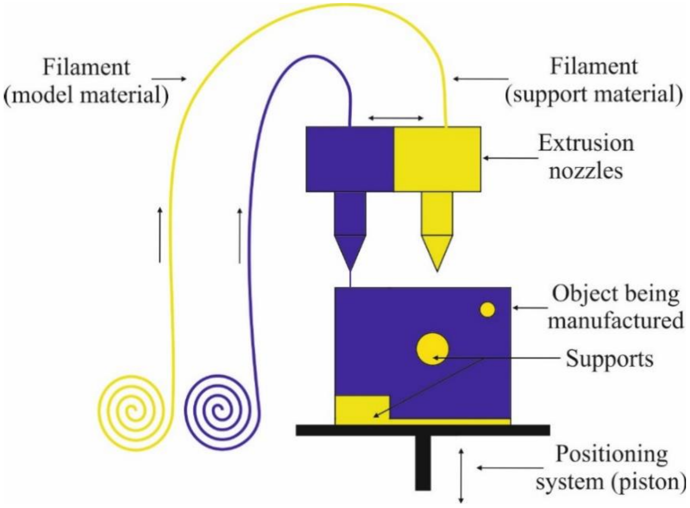

Figure 2. Fused deposition model (FDM) [12,13]

Originally employed for producing affordable prototypes and demo models, FDM technology has progressed to crafting top-notch functional prototypes and conceptual models using diverse thermoplastic materials. It now facilitates the use of a minimum of two materials—support material and manufacturing material. Typically, the support material exhibits inferior mechanical properties compared to the part material, enabling straightforward mechanical extraction. Moreover, the support material is easily soluble [11,12,13].

III. What are the key factors affecting energy efficiency in FDM systems?

In the quest to enhance energy efficiency within Fused Deposition Modeling (FDM) systems, it is imperative to consider several key factors that significantly influence the overall energy consumption and sustainability of these processes. Firstly, the design of the product itself emerges as a primary factor, as it directly affects the complexity and duration of the printing process, thereby impacting the energy requirements of FDM systems [14]. Alongside, the choice of materials plays a critical role; different materials require varying amounts of energy for proper transformation and deposition, with some necessitating higher levels of heat absorption than others [14]. This is further compounded by the necessity of choosing optimal process parameters, such as print speed and temperature, which must be meticulously calibrated to balance energy efficiency with the desired quality of the printed parts [15]. Moreover, the implementation of energy-saving methodologies, including the refinement of the machine's operational parameters and the utilization of materials with better thermal properties, not only contributes to the reduction of energy consumption but also enhances the quality of the final product [15]. Therefore, understanding and optimizing these key factors product design, material selection, process parameters, and energy-saving techniques are essential for advancing the energy efficiency of FDM systems.

IV. How can parameters in FDM be optimized for better energy efficiency?

Building on the understanding that the design of products significantly impacts the energy efficiency of Fused Deposition Modeling (FDM) systems, it's crucial to explore how specific parameters within the FDM process can be optimized for better energy outcomes. Research highlights the importance of considering the printing method, layer thickness, and the necessity of support structures as key parameters for optimization [14]. This approach is supported by findings that suggest optimizing these parameters can lead to substantial energy and material savings, as evidenced by an analysis of popular designs on Thing verse, which projected a potential savings of 91.51 tons of material and 210,000 kWh of energy [16]. Furthermore, techniques such as employing reduced line support and lightning infill have been pinpointed as effective strategies for achieving these savings [16]. This clearly underscores the pivotal role that parameter optimization plays in enhancing the energy efficiency of the AM process, aligning with the broader goal of sustainable manufacturing practices. By meticulously adjusting these parameters, not only can the immediate energy consumption be reduced, but it also contributes to a more resource-efficient use of materials, aligning with the objectives of reducing the environmental footprint of additive manufacturing [16].

V. What are the recent advancements in technology that contribute to energy efficiency in FDM additive manufacturing?

Building on the foundation of optimizing design parameters for energy efficiency in FDM additive manufacturing, recent advancements have further broadened the scope of enhancing energy sustainability in this field. A notable area of exploration is the development of novel materials designed to improve the energy-absorbing qualities of printed objects, which directly contributes to the efficiency of the manufacturing process itself [14]. Concurrently, the potential of integrating renewable energy sources into the additive manufacturing infrastructure presents a significant advancement towards achieving greater energy efficiency. This approach not only aligns with the global shift towards sustainable energy but also opens new avenues for reducing the carbon footprint of the additive manufacturing sector [14]. Moreover, the proposal of a holistic framework that encapsulates the entire life cycle of the additive manufacturing process from design optimization and material selection to advanced control systems and energy management strategies underscores a comprehensive approach to tackling energy inefficiency [14]. This multi-faceted strategy emphasizes not only the importance of innovative material science and renewable energy adoption but also the critical role of sophisticated process control and management in enhancing the energy efficiency of FDM additive manufacturing processes.

VI. Framework for Energy Efficiency in Additive Manufacturing:

The literature does not adequately portray the intricate and multifaceted nature of achieving energy efficiency in additive manufacturing (AM). Existing research primarily concentrates on individual remedies for particular aspects of the problem. Instead of taking a comprehensive approach to studying energy efficiency, many cases focus on specific aspects. This section aims to address this issue by examining all aspects of energy efficiency. There are various factors within the AM process that have a direct or indirect impact on energy efficiency. To achieve energy efficient and sustainable manufacturing through the use of additive manufacturing (AM), it is crucial to take a comprehensive approach that encompasses the entire life cycle of the AM process [17]. Additionally, it is important to establish a correlation between these efforts.

The literature lacks a significant discussion on the relationship between energy efficiency and product quality. In today's manufacturing industry, where sustainability is of utmost importance, this topic is noticeably overlooked. Maintaining competitiveness in the industry necessitates the use of an energy efficient additive manufacturing process to produce high-quality parts [18]. In order to ensure the most effective manufacturing method is chosen, it is necessary to provide adequate justification when comparing it to traditional machine usage. Taking these factors into account, we have created a comprehensive framework, as depicted in the AM stages that impact energy efficiency and sustainability are depicted in Figure 3.

The framework outlined in [19] highlights the crucial elements that impact energy efficiency in additive manufacturing (AM). These factors encompass product design, material composition and structure, energy consumption during the production of AM materials, slicing process, the AM process itself, post printing process, and the potential for reusing AM materials.

To enhance the energy efficiency of AM, it is crucial to implement strategies that reduce energy consumption at every stage. This can be achieved through various means, including optimizing the design, utilizing energy-efficient machinery, choosing materials that promote energy conservation, and optimizing the printing process. The design of the product plays a pivotal role in determining the energy efficiency of AM. In order to prioritize energy efficiency, it is essential to thoroughly record and analyze all design elements that have the potential to affect it. When evaluating different mechanical and design options, the utmost importance should be placed on selecting the most energy efficient solution. The second aspect involves the composition and format of the material, which are the functional requirements.

Figure 3. Stages in AM that affect energy efficiency.

The development of materials for additive manufacturing should prioritize energy efficiency. One area that has not received much research attention is the aspect of energy efficiency, specifically in relation to the absorption of energy or heat and the energy requirements for material transformation. The manufacturing process of AM materials involves a significant amount of energy, both in their production and in shaping them into the desired form. The efficiency of energy usage is influenced by the slicing of the part, as it plays a crucial role in determining the pathways. In addition to energy efficiency, the selected paths that the AM nozzle will adhere to the mechanical properties of the part are also influenced by the sequence in which the components are arranged. Hence, it is important to consider both the composition and arrangement when determining the mechanical properties. It is crucial to tackle all of these elements concurrently, as they may potentially contradict one another. For example, while enhancing energy efficiency could result in a reduction in mechanical. The process of additive manufacturing (AM) involves a reciprocal relationship between design and properties. Following this, the next step is the implementation of the AM process itself. To minimize energy usage, it is imperative to utilize highly efficient equipment [20]. Additionally, by improving the functionalities of additive manufacturing (AM) machines, the amount of printing needed can be reduced. One of the notable advantages of AM is its ability to reduce the required energy for the overall process by saving time. However, it is widely acknowledged that AM is not without flaws, particularly when it comes to surface quality and achieving precise dimensions.

To enhance the energy efficiency of additive manufacturing (AM), various tactics can be implemented to minimize energy consumption across the entire process. Here are a few suggestions:

- To consume less energy in additive manufacturing (AM), an effective approach is to optimize the design [20]. By minimizing the use of materials and energy during the creation process, energy consumption can be significantly reduced. When optimizing, it is crucial to take into account the printing method, layer thickness, and other important factors. Support structures are essential in the realm of AM. Additionally, an effective method for conserving energy in this field is to employ machines that are energy efficient.
- Newer models of AM machines are more energy-efficient compared to their older counterparts. The utilization of these materials has the potential to greatly reduce energy consumption. Opting for energy saving materials is a crucial factor in determining the overall energy impact.
- The energy efficiency of additive manufacturing (AM) can be enhanced by utilizing materials that require less energy for production. This can be achieved by using bio-based polymers or recycled materials, which can significantly reduce the overall energy consumption during the manufacturing process.
- Enhancing the printing process can lead to a reduction in material development. The conservation of energy can be achieved by implementing measures such as reducing the speed of the printing process and ensuring efficient maintenance.

We emphasize a comprehensive approach to energy efficiency in additive manufacturing, which includes maintaining an optimal temperature and reducing reliance on support structures. Our framework encompasses all aspects of energy conservation in this process. The significance of taking into accounts every aspect and how they intertwine during the additive manufacturing process cannot be overstated. This all-encompassing approach sets the stage for further exploration and real-world implementations. The framework presented in this section has immense value for both research and the advancement of a more sustainable and energy efficient manufacturing industry. This framework can act as a roadmap for researchers, aiding in the identification of practical applications.

By identifying the openings and possibilities within the realm of energy-efficient additive manufacturing, this analysis can effectively direct forthcoming investigations. Furthermore, it can play a crucial role in structuring and arranging research endeavours. This framework allows practitioners to present their findings in a more organized and thorough manner. By adhering to the framework, practitioners can systematically assess and enhance energy efficiency in additive manufacturing processes. This approach offers a methodical way to identify specific areas that require improvement. The framework outlined here enables the identification of inefficiencies, the formulation of optimization strategies, and the on-going monitoring of their effectiveness. Additionally, this comprehensive approach supports decision-making by offering a complete understanding of the various factors that impact energy efficiency in additive manufacturing. This knowledge facilitates the selection of the most energy-efficient methods and technologies.

VII. Conclusions:

This mini review has provided an in-depth analysis of optimizing energy efficiency and parameters in Fused Deposition Modeling (FDM) additive manufacturing systems. The research explored various facets of energy consumption within the additive manufacturing (AM) process, emphasizing the significance of energy conservation in the era of sustainable manufacturing. Through an examination of key factors affecting energy efficiency in FDM systems, including product design, material selection, process parameters, and energy-saving techniques, it became evident that a holistic approach is essential for achieving significant reductions in energy consumption. Furthermore, the optimization of specific parameters within the FDM process, such as printing method, layer thickness, and support structures, was highlighted as crucial for minimizing energy usage while maintaining product quality.

Recent advancements in technology, such as the development of novel materials with improved energy-absorbing qualities and the integration of renewable energy sources, were identified as promising avenues for further enhancing energy efficiency in FDM additive manufacturing. The proposal of a comprehensive framework encompassing all stages of the AM process emphasized the importance of considering energy efficiency from design to post-printing processes. The outlined framework serves as a roadmap for researchers and practitioners, facilitating the identification of inefficiencies, formulation of optimization strategies, and on-going monitoring of their effectiveness. By adhering to this comprehensive approach, stakeholders can systematically assess and enhance energy efficiency in additive manufacturing processes, ultimately contributing to a more sustainable and energy-efficient manufacturing industry.

This mini review underscores the critical importance of energy efficiency in additive manufacturing systems, providing valuable insights and guidance for future research and real-world implementations in the pursuit of sustainable manufacturing practices.

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