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An Experimental Investigation on Surface Roughness of Laser Beam Machining of Aluminium Alloy

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Abstract

Laser beam machining (LBM) is a cutting-edge technique widely utilized for precision machining of advanced materials. This experimental investigation focuses on the surface roughness of aluminum alloy (Al 6061) during LBM. The study systematically examines the impact of process parameters such as laser power, cutting speed, and gas pressure on surface roughness (Ra). The significance of surface roughness in determining the quality and functionality of machined components is emphasized. The experimental setup employs the AMADA LCG3015AJ laser beam machining system with a 6000W fiber laser, ensuring precision and control over various parameters. A factorial design matrix, incorporating factors like laser power and scanning speed, is strategically employed. Response Surface Methodology (RSM) aids in constructing a predictive model for surface roughness, facilitating optimal conditions for desired finishes. The experimental runs, conducted at M/s Anand Lasers, Pune, India, involve the systematic alteration of parameters, and surface roughness is evaluated using advanced metrology methods. Statistical analysis, including ANOVA, unveils significant contributors to surface roughness, guiding process optimization. The final expression incorporating coded factors provides a comprehensive understanding of the relationship between process parameters and surface roughness. The results showcase the intricate dynamics of LBM on aluminum alloy surfaces. The study contributes valuable insights for optimizing machining processes, enhancing surface quality, and advancing precision manufacturing.

Keywords: Surface roughness, aluminium alloy, laser beam machining, Anova, alloy, thermal analysis, characterization, processing and manufacturing, properties and performance, mechanical properties

INTRODUCTION

Laser beam machining (LBM) has evolved as a flexible and effective production technology, giving various benefits over traditional machining methods. This non-contact, precision-based approach permits the precise shape and slicing of a broad range of materials, including ceramics, plastics, and metals. Due to the growing need for lightweight and high-strength materials in the aerospace, automotive, and electronics sectors, the laser-assisted machining of aluminum alloys has attracted substantial attention among diverse industrial applications. Surface roughness (R_a) is critical in influencing the functioning and performance of machined components. It has an immediate impact on the mechanical characteristics, wear resistance, and fatigue life of the final product. In businesses where rigorous quality requirements and tight

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tolerances are demanded, achieving the proper surface roughness is very important. In order to improve the overall performance and dependability of the machined components, it is crucial to study and optimize the surface roughness during LBM of aluminum alloys. Understanding the complicated interactions between the laser beam and the material of the work piece is crucial to the success of LBM. Multiple variables, including laser power, beam spot size, scanning speed, and material parameters, affect the machining process and, subsequently, the surface roughness. Experimental studies have a significant role in elucidating the complicated dynamics of the laser-material interaction and identifying the underlying variables influencing surface roughness.

This study report gives a comprehensive experimental analysis into the surface roughness of laser-machined aluminum alloy. The purpose of this study is to examine exhaustively the impacts of important process factors, such as laser power, gas pressure and cutting speed on the R_a of machined aluminum alloy. Utilizing a state-of-the-art LBM system permits fine control of process parameters and ensures reliable and consistent findings for this inquiry. Advanced metrology methods are used to assess surface roughness, yielding accurate and complete data for analysis. This study will not only improve our basic understanding of laser beam machining, but it will also provide vital insights for companies trying to optimize the surface roughness of aluminum alloy components. Further, this research study aims to make a substantial contribution to the area of laser beam machining by illuminating the complicated interactions between process parameters and R_a in the context of aluminum alloy machining. This study's results have the potential to enhance the production capabilities of laser beam machining and open up new possibilities for the manufacture of high-performance aluminum alloy components in a variety of industrial sectors. The literature review examines the current body of knowledge and research on LBM of aluminum alloys and its effect on surface roughness. In order to build a strong basis for this work, a thorough search of scholarly papers, scientific journals, conference proceedings, and other pertinent academic sources was done. Beginning with an explanation of the underlying concepts of laser beam machining and its advantages over traditional machining processes, the review then discusses the benefits of laser beam machining. The paper next examines prior research on surface roughness optimization in laser machining, emphasizing the major process factors and their influence on surface quality. In addition, research on the thermal and material characteristics of aluminum alloys and their influence on laser machining results is included. Special emphasis is placed on developments in laser technology and metrology methods used to evaluate surface roughness. The synthesis of these prior studies not only exposes the existing gaps in knowledge, but also gives crucial insights for formulating the experimental investigation's study objectives.

Machining Techniques

Aluminum alloys, known for their distinctive properties and economic feasibility, play a crucial role in various engineering applications, spanning industries such as automotive, aerospace, and electronics. The machining process is integral to the fabrication and manufacturing of these alloys, gaining heightened importance in sectors like aerospace where precision and accuracy are paramount. In such applications, non-conventional machining techniques are employed to achieve intricate machining with a high degree of accuracy. Laser beam machining (LBM) emerges as a cost-efficient solution, offering superior processing rates compared to conventional techniques, making it a promising non-conventional machining approach. Unlike conventional machining where mechanical properties are the primary focus, LBM hinges on the thermo-physical and optical properties of the material. This article delves into the intricate details of these properties concerning aluminum and its alloys, shedding light on their interaction with a laser beam. The discussion extends to various types of lasers and their unique characteristics, which are strategically leveraged in different machining scenarios. The interplay of laser characteristics and parameters governs diverse material removal phenomena during machining, allowing for precise control. Within the realm of aluminum and its alloys,

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LBM is predominantly employed for drilling, cutting, and milling operations. Figure 1 illustrates these operations, showcasing the versatility of LBM in manipulating the material.

Additionally, operations like turning, grooving, scribing, and marking can be effectively executed with optimized processing parameters. The article explores different approaches for each machining operation, emphasizing the dimensionality involved in processes like laser drilling. Understanding the intricacies of LBM techniques requires a comprehensive analysis of process parameters and their impact on performance parameters. The article serves as a valuable resource by providing insights into the relationship between these parameters, offering general guidelines for practitioners conducting LBM trials on aluminum and its alloys. As industries embrace miniaturization trends, micromachining becomes increasingly prevalent across diverse fields. LBM, when applied to micromachining, allows for operations at micron and submicron levels, ensuring high accuracy and superior surface finishing. The article underscores the use of ultrashort pulse lasers, operating in the picosecond and femtosecond range, which induce distinct mechanisms of material removal. The final section of the article meticulously details these mechanisms, providing a comprehensive overview of the intricate world of micromachining with LBM. The Paper not only highlights the significance of aluminum alloys in engineering applications but also underscores the pivotal role of LBM in their machining processes. By delving into the material properties, laser characteristics, and machining operations, the article equips readers with a holistic understanding of LBM's application in the realm of aluminum and its alloys, offering valuable insights for both researchers and practitioners in the field.

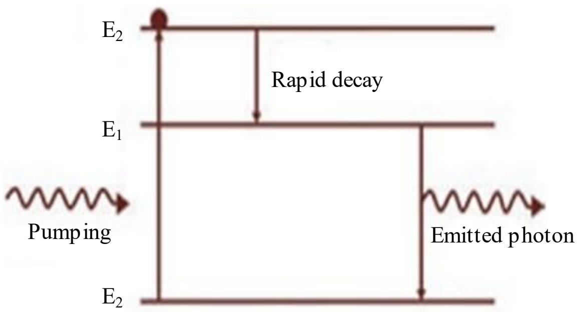

Figure 1. Schematic of excitation of an electron to higher energy level E2 and emission of the photon after rapid decay, leading to stimulated emission [1].

Lasers System

The evolution of lasers, a groundbreaking technological advancement, traces its roots to pivotal concepts developed in the early 20th century. The understanding of wave-particle duality and the electromagnetic nature of light laid the foundation for the concept of stimulated emission of radiation across electromagnetic waves. This concept, applied to light in 1957, culminated in the birth of lasers, with the term itself standing as an acronym for "light amplification by stimulated emission of radiation." The inaugural laser, utilizing stimulated optical radiation in ruby (chromium in corundum), materialized in 1960. Distinct from conventional light sources, lasers exhibit high coherence, monochromaticity, and phase alignment, resulting in an amplified and focused radiation beam. The energy level differences within atoms play a crucial role in laser operation. When an atom absorbs a photon of precise frequency, it enters an excited state, prompting the transition of an electron from a lower to a higher energy level. Subsequently, the excited electron returns to its ground state, emitting a photon with the same frequency as the incident one. This process, known as stimulated emission, can trigger a chain reaction as emitted photons may stimulate further emissions, fostering a coherent and energetic radiation output.

The concept of population inversion, where the higher energy level contains more electrons than the lower energy state, is fundamental to laser operation. Achieving population inversion

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involves pumping the atoms to the higher energy state, and when stimulated emission returns them to the lower energy state, laser action occurs. Despite being categorized as monochromatic, lasers possess a narrow band of closely spaced spectral lines, differing from the broad emission spectrum of ordinary light sources. The lasing medium dictates the temporal mode capability, enabling lasers to operate in continuous wave (CW) or pulse mode. Spatial mode profiling, characterized by transverse electromagnetic (TEM) modes, plays a crucial role in laser functionality. For machining applications, the Gaussian power distribution with the fundamental TEM00 mode is commonly employed. This mode features a uniform phase front and a smoothly dropping intensity from the center, making it ideal for precision machining purposes. Lasers represent a transformative technology with a rich history rooted in fundamental scientific concepts. Their coherent and focused radiation has found diverse applications, including machining processes. Understanding the principles behind laser operation, including population inversion and spatial modes, is paramount for harnessing their capabilities in various industrial and scientific endeavors.

$$I\,(r) \;=\; Ioexp\,[-\frac{2r2}{w2}]$$

In the realm of laser beam machining, the surface roughness of machined materials plays a pivotal role in determining the overall quality and functionality of the finished product. The investigation delves into the intricate factors influencing surface roughness, specifically in the context of aluminum alloy. The passage introduces essential parameters, such as the radius of the laser beam (r), the incident beam intensity (I0), and the radial distance-dependent intensity (I rð Þ), where w signifies the radius at which the intensity diminishes to 13.5% of the peak intensity. Understanding these parameters is crucial as the material removal at different regimes is not uniform due to the gradual decrease in intensity towards the beam's periphery. Consequently, the use of optical diffracting elements is explored to transform the Gaussian intensity distribution into a more even top hat distribution, as illustrated in Figure 2. This shift in intensity distribution holds significant implications for optimizing surface roughness during laser beam machining processes.

$$I\,(r) \;=\; Ioexp\,[-2\left(\frac{2}{w}\right)n]\;(n \to \infty)$$

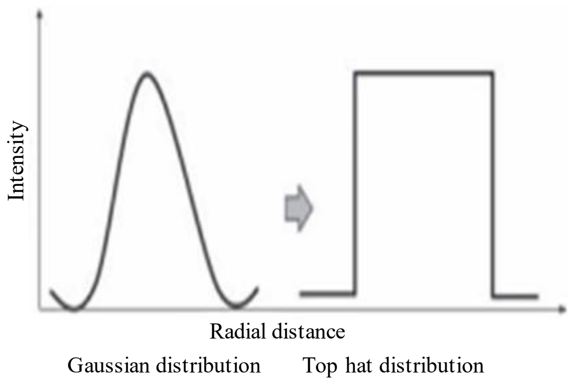

Figure 2. Schematic of Gaussian and top hat intensity distribution [1].

Lasers, integral to the field of laser-assisted machining, exhibit diverse characteristics based on the medium in which they operate. The primary laser types include solid-state lasers, gas lasers, semiconductor lasers, and dye lasers. Nd: YAG, a solid-state laser, and CO_2 gas lasers are commonly employed in laser-assisted machining. Additional laser types, such as excimer lasers, high power diodes, and fiber lasers, are utilized for their low wavelength capabilities. However, these lasers often lack high average power output. CO_2 lasers, operating at a wavelength of 10.6 mm in the infrared spectrum, possess notable advantages, including high average beam power, superior beam quality, and efficiency. These attributes make them well-suited for swiftly cutting

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thicker sections (>10 mm, or 0.4 in.). On the other hand, Nd: YAG lasers excel in the pulse mode, generating high power suitable for precision metal cutting at thicknesses unattainable with CO_2 lasers. Their smaller wavelength enables the production of a small spot size on the workpiece, contributing to a quality cut with factors such as kerf width, heat-affected zone (HAZ), and surface roughness being affected. Optical fibers play a crucial role in transporting the laser to the workpiece over substantial distances, but this process introduces energy loss, Rayleigh scattering losses, and beam spread. Consequently, only specific laser types are feasible for transmission via fiber optics. The beam product parameter (BPP) serves as a critical measure, defining the focusing quality of the laser beam. Calculated as the product of the divergence angle (γ) and the radius of the collimated beam (w), BPP is instrumental in assessing the overall performance and precision of laser-assisted machining systems. Understanding these diverse laser characteristics is fundamental for optimizing the surface roughness of materials, particularly in experimental investigations such as laser beam machining of aluminum alloy.

Table 1. Nontraditional Machining Techniques [1].

Process	Energy Transfer	Characteristics/Application	Performance Parameters
USM	Mechanical	1. Usually applied to non-conductive harder materials like ceramic (40–60 HRC). 2. No heat generation. 3. Applicable when hardness is > 45 HRC. 4. Operations: drilling, milling, grinding.	MRR: 0.025–25 (mm^3/min) Surface Finish: 0.25–0.75 mm Tolerance: 7–25 mm
AJM	Mechanical	1. Useful in electronic device manufacturing (glass wafers, plastics). 2. Suitable for brittle, heat-sensitive materials. 3. Cutting intricate cavities in thin sections of brittle materials. 4. Low initial investment cost.	MRR: 10–20 Surface Finish: 0.25–1.25 mm Tolerance: 50–125 mm
WJM	Mechanical	1. Can cut any class of material. 2. Cuts stacked materials. 3. No heat affected zone, recast layer, or dross formation. 4. High tool wear and operating cost. 5. Surface contamination with abrasive.	MRR: 0.5–3.5 Tolerance: 100–250 mm
EDM	Electrical	1. Machining only electrically conductive materials. 2. Burr-free machining, high machining rate. 3. High edge quality.	MRR: 0.1–10 Surface Finish: 0.25–12.7 mm Tolerance: ± 2.5 mm
PAM	Electrical	1. High machining and material removal rate. 2. Rounded edges. 3. High initial cost, lower operating cost. 4. Profile cutting, especially of aluminum.	MRR: 30000–75000 Surface Finish: 5–75 (rough surface) Tolerance: ± 800 (poor tolerance)
ECM	Electro-Chemical	1. Cuts electrically conductive materials. 2. Intricate machining in a single pass. 3. Operations: turning, drilling, broaching, grinding, deburring, punch cutting. 4. Hydrogen embrittlement issue.	MRR: 10000–16000 Surface Finish: 0.12–2.5 mm Tolerance: 25–50 mm
EBM	Electro-Thermal	1. Cuts reactive metals (Mg, Al) with high surface finish. 2. Used for drilling small holes in diesel injection nozzles and air brakes at high rates. 3. Requires vacuum generation. 4. High investment cost, skilled operator required.	MRR: 0.5–0.75 Surface Finish: 0.5–12.5 mm Tolerance: 5–50 mm
LBM	Electro-Thermal	1. Operations: cutting, drilling, milling, grooving, turning, micromachining. 2. High machining rate, surface finishing. 3. Machining all material classes by changing parameters. 4. Burr-free, recast layer-free, dross-free with picoseconds and femtoseconds.	MRR: 5–300 Surface Finish: 0.02–2.5 mm Tolerance: 0.025–6.3 mm

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BPP = $\theta . \omega$

Laser beam machining (LBM) is a cutting-edge technique in the materials processing industry, utilizing the unique characteristics of lasers for precise material removal. Table 1 provides an overview of key characteristics of lasers commonly employed in this industry. The interaction between the laser beam and the material is a complex process, involving various optical phenomena such as reflection, transmission, absorption, refraction, and scattering. In laser-assisted machining, the thermal process leads to material removal through mechanisms like melt ejection, vaporization, or ablation. Understanding these laser-material interactions is pivotal to comprehending the intricate process of material removal in laser machining. When the laser interacts with the material, a cascade of optical phenomena occurs, influencing the substrate at a fundamental level. These effects include temperature evolution, thermal stresses, shear stress, phase transformations, capillary pressure in a liquid state, Marangoni effects, and dilution effects, as depicted schematically in Figure 3. Notably, the laser beam-material interaction zone is typically much smaller (ranging from a few square microns to a few square millimeters) compared to the overall dimensions of the workpiece. Consequently, a small region on the workpiece undergoes rapid heating (heating rates ranging from 10^3 to 10^5 K/s), while the surrounding material remains at room temperature. This creates a substantial thermal gradient, accompanied by cooling rates of a similar magnitude to the heating rates. The kinetics of the process play a pivotal role in shaping the laser-material interaction, with the material's response influenced by various physical phenomena.

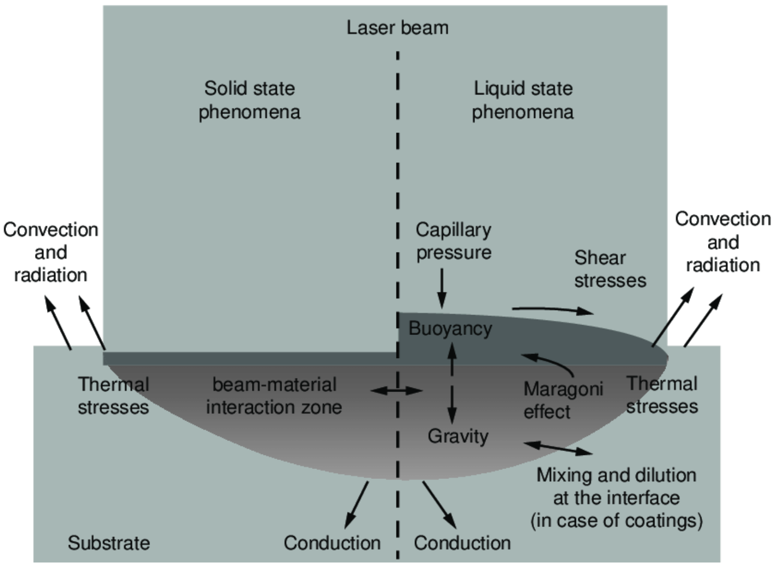

Figure 3. Schematic representation of various phenomena taking place during laser-material interaction [1].

The efficacy of LBM in a specific application hinges on factors such as the pulsing and focusing of the laser beam, as well as the optical and thermo-physical properties of the workpiece. Parameters like reflectivity, absorption coefficient, thermal conductivity, specific heat, and heat of vaporization of the material significantly impact the outcome. Absorptivity, a crucial parameter in laser-material interaction, is determined by Beer-Lambert's law. This law expresses the absorption of a given material with a specific absorption coefficient in response to laser radiation. The experimental investigation on surface roughness of laser beam machining of aluminum alloy delves into the intricate world of laser-material interactions. The thermal processes involved, including melt ejection, vaporization, and ablation mechanisms, underscore the significance of understanding the optical phenomena at play. As the laser beam interacts with the material, the resulting effects on temperature, stress, and phase transformations contribute to

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the overall success of laser machining. This study emphasizes the importance of considering parameters like pulsing, focusing, and material properties for optimal outcomes in laser beam machining applications.

Conventional Machining of Aluminum Alloys

Traditional machining methods have long been the cornerstone of material removal processes, relying on direct contact between the tool and the workpiece. The predominant mechanism involves shear force to fracture or chip off the material. Typically, the tool's hardness surpasses that of the workpiece by 30-50%, facilitating the efficient removal of material. However, the machinability of a material is influenced by a myriad of factors, including chemical composition, microstructure, grain size, fracture toughness, elastic modulus, thermal conductivity, thermal expansion, work hardening, and fabrication techniques. Machinability, a crucial aspect, is defined as the ease with which material can be removed by a given tool with high efficiency and low cost. Aluminum and its alloys, being widely used materials, undergo various conventional machining operations to achieve specific workpiece geometries. Common operations include turning, milling, and drilling, supplemented by an array of others such as boring, broaching, planning, shaping, reaming, burnishing, tapping, threading, sawing, grinding, honing, grooving, and lapping. While manual machining operations persist, the prevalence of computer numerical control (CNC) machines has surged due to their precision and accuracy. The Swiss style of machining, featuring a sliding headstock arrangement supplying material to the rotating side, is favored for intricate machining tasks.

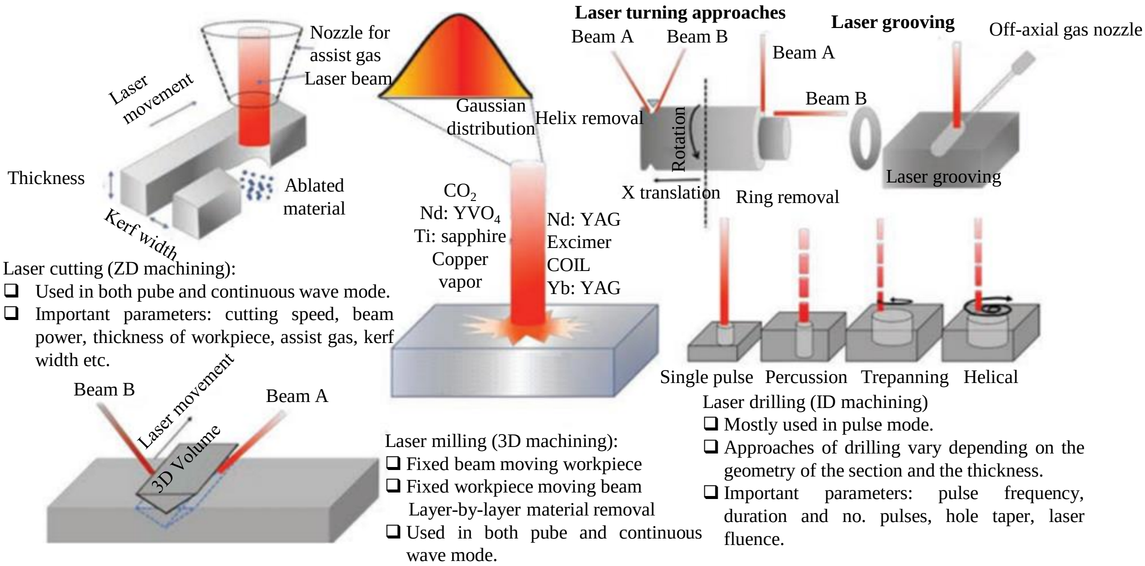

Figure 4. Laser beam machining of aluminum alloys [1].

Despite the effectiveness of conventional machining, it faces limitations such as cutting speed constraints, challenges in achieving precise surface finishes and accuracy, particularly with small workpiece, and the issue of short tool life due to high wear, contributing to elevated costs. The choice of tool material for each machining operation varies based on the alloy being processed. Furthermore, traditional machining introduces undesirable mechanical and thermal residual stresses due to friction at the machined surface and subsurface regions. Materials intended for machining must exhibit properties suitable for the process. Excessive ductility or malleability, as well as excessive hardness or brittleness, pose challenges to machinability within conventional techniques. Recognizing these limitations, non-conventional machining techniques have emerged as viable alternatives over the past few decades. A defining characteristic of these techniques is the absence of direct contact with the workpiece, as opposed to traditional methods.

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Instead, energy is transferred in various forms—mechanical, thermal, chemical, and electrical—to the material, shaping it accordingly. While the costs associated with non-conventional techniques tend to be higher compared to conventional methods, they offer distinct advantages. These techniques provide higher accuracies and superior finishing of the workpiece, effectively addressing the drawbacks of traditional machining.

Importantly, they can be applied to both soft materials (such as aluminum, copper, brass, and steel) and extremely hard materials (including carbide, borides, oxides, and nitrides). Unlike conventional methods, non-conventional techniques eliminate the need for hard tools, allowing delicate machining operations without the material property constraints inherent in traditional approaches. The ongoing research and development efforts in non-conventional machining are geared towards enhancing cost efficiency, ensuring the continued viability of these techniques in the industrial sector. As industries seek more precise and efficient machining solutions, the evolution of non-conventional techniques holds promise for addressing the challenges posed by traditional methods (Figure 4).

Non-Conventional Machining of Aluminum Alloys

Non-conventional machining techniques have revolutionized the field of material processing by offering alternative methods that do not rely on direct tool contact with the workpiece. These techniques exhibit superior machining capabilities compared to traditional methods, utilizing various forms of energy such as mechanical, thermal, chemical, and electrical to shape the material. The focus of this experimental investigation lies in exploring the surface roughness of aluminum alloy subjected to laser beam machining (LBM), which falls under the category of beam and radiation-based non-conventional techniques.

Mechanical Energy-Based Techniques: Mechanical energy-based non-conventional machining techniques operate by utilizing forces that do not require direct physical contact with the workpiece. Ultrasonic machining (USM), water jet machining (WJM), abrasive jet machining (AJM), and abrasive water jet machining (AWJM) are notable examples in this category. These methods leverage mechanical vibrations, high-velocity abrasive particles, or a combination of both to erode and shape the material. The absence of direct tool contact allows for intricate and precise machining, particularly beneficial for delicate materials like aluminum alloys.

Electrical Energy-Based Techniques: Electrical energy-based non-conventional machining involves the utilization of electrical discharges to remove material from the workpiece. Electro-discharge machining (EDM) and plasma arc machining (PAM) are prominent representatives in this category. These methods generate high-energy electrical discharges to achieve material removal, making them suitable for intricate and complex shapes. The ability to work on electrically conductive materials, such as aluminum alloys, positions these techniques as effective alternatives.

Beam and Radiation-Based Techniques: The category of beam and radiation-based non-conventional machining includes laser beam machining (LBM), electron beam machining (EBM), and ion beam machining (IBM). Laser beam machining, the primary focus of this investigation, utilizes the concentrated energy of a laser beam to melt or vaporize material from the workpiece. This precise and controlled process is particularly advantageous for materials like aluminum alloys, where heat-affected zones need to be minimized.

Electrical and Chemical Energy-Based Techniques: Electrical and chemical energy-based techniques combine both electrical discharges and chemical reactions for material removal. Electrochemical machining (ECM), electrochemical grinding and drilling, and electro-chemical spark machining (ECSM) fall into this category. The synergy of electrical and chemical processes

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enhances the machining capabilities, providing an effective solution for materials with complex geometries. Additionally, chemical energy-based techniques like chemical milling, photochemical milling, and biochemical machining contribute to the arsenal of non-conventional machining options.

Micro and Nano-Machining Processes: Several non-conventional machining techniques specialize in micro and nano-level machining, catering to the increasing demand for precision in modern industries. Abrasive flow machining (AFM), magnetic abrasive finishing (MAF), magnetic-rheological finishing (MRF), magnetic-rheological abrasive flow finishing (MRAFF), magnetic float finishing (MFF), elastic emission machining (EEM), and micromachining using lasers are examples that fall under this category. These techniques offer unparalleled precision and control, making them suitable for applications where minute details matter.

The exploration of these non-conventional machining techniques is essential for understanding their applicability to different materials and the specific advantages they offer. In this experimental investigation, the focus shifts to laser beam machining (LBM) and its impact on the surface roughness of aluminum alloy, a material commonly employed in various industries for its lightweight and corrosion-resistant properties.

Laser Beam Machining (LBM) of Aluminum Alloy

Laser beam machining (LBM) is a non-conventional technique that utilizes a highly focused laser beam to remove material from the workpiece. The intense energy of the laser beam results in melting, vaporization, or even sublimation of the material, leading to precise machining. LBM offers several advantages, including minimal tool wear, high precision, and the ability to process a wide range of materials, including aluminum alloys.

Principles of Laser Beam Machining

The principles governing laser beam machining involve the conversion of electrical energy into coherent light, typically through the process of stimulated emission of radiation. The laser beam generated is then focused on the workpiece using lenses or mirrors, achieving a high energy density at the focal point. This concentrated energy interacts with the material, causing rapid heating and subsequent material removal. The efficiency of LBM is influenced by various parameters, including laser power, beam diameter, scanning speed, and focal length. Adjusting these parameters allows for control over the depth and width of the machined region. In the case of aluminum alloys, the goal is to achieve precise machining while minimizing undesirable effects such as thermal distortion and heat-affected zones.

Laser Beam Machining

Laser Beam Machining (LBM) stands out as a prominent non-conventional machining technique, leveraging electro-thermal energy for efficient material removal. This method is particularly advantageous when dealing with hard and brittle materials, where conventional techniques often incur high tool material losses due to elevated wear rates, making the machining process prohibitively expensive. In contrast, LBM utilizes the optical and thermophysical properties of the material itself, minimizing material loss and demonstrating superior process efficiency compared not only to conventional methods but also to other non-conventional machining techniques, especially when excluding the initial capital investment. The versatility of LBM extends to its ability to machine a diverse range of engineering materials, including metals, ceramics, composites, and glasses. The technique's rapidity in material removal sets it apart from alternative non-conventional methods, such as water jet abrasive machining, as highlighted in Table1, which summarizes the distinctive characteristics and performance parameters of various non-conventional machining methods in comparison to LBM.

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Table 2. Chemical Composition of AL6061.

Element	Al	Si	Cu	Mg	Cr
Weight (%)	97.9	0.60	0.28	1.0	0.20

Furthermore, LBM facilitates the machining of components with intricate shapes and a wide range of dimensions, requiring minimal support for the workpiece. The application of lasers in micromachining further enhances the LBM technique's capabilities, expanding its scope and applicability in manufacturing processes. Continuous research endeavors have played a pivotal role in enhancing the economic feasibility of the LBM process within the realm of non-conventional machining. As a result, LBM has emerged as a cost-effective and efficient solution for machining a variety of materials, contributing to its widespread adoption in industrial applications. The evolving landscape of non-conventional machining processes positions LBM as a forefront contender, emphasizing its significance in advancing precision manufacturing technologies.

RELATED WORK

LBM can be utilized on a wide variety of materials [2]. Since the machining process of a laser cutter is regulated by the interface between the work piece's material and the laser beam, it is difficult to cut materials like aluminum, copper, and their alloys [3]. Aluminium and aluminium alloys constitute highly adaptable engineering materials that are extensively used in the industry due to their special and inherent performance [4]. Khed et al. experimented with 3 mm thick aluminum alloy 8011 to investigate the impact of cutting speed, laser power and gas pressure on kerf width and R_a [5]. They discovered that cutting Aluminium Alloy 8011 was challenging due to its reflectivity. The experiment design was created using the technique of response surface methodology (RSM), and the regression method was then utilized to analyze it. Any degree of power can be used to operate at lower speeds and gas pressures to achieve the lowest surface roughness, and lower speeds and gas pressures can be used to get the smallest kerf width. Manjoth et al. worked on LBM of an In-situ synthesized composite metal matrix made of Al7075–TiB2. They evaluated the influence of optimizing LBM parameters on the surface roughness, dimensional accuracy, and volumetric material removal rate (MRR) of composites [6]. Gas pressure, standoff distance, and cutting speed were examined as three levels of input variables, while air was used as the supporting gas and power and nozzle diameter were remained constant. Results reveal that cutting speed is the most critical parameter for R_a. Gas pressure is the most important characteristic for volumetric material removal, proceeded by standoff distance and cutting speed. Standoff distance is the most important factor for dimensional error, proceeded by gas pressure and cutting speed. Leone et al. studied effect of variables on the kerf geometry, laser cutting tests using a pulsed laser were acted upon on sheets of 6061-T6 AA that were 1 mm thick [7]. Depending on the direction of the beam's travel and the length of each pulse, the maximum cutting speed ranges between 1200 and 450 mm/min. It increased the laser beam is when moved down the circular focal footprint's minor axis and with larger pulse durations. By using a long pulse duration, it is possible to create a nearly perpendicular kerf ($Ta<4°$). A 150-W multimode lamp powered laser was used by the Leone et al. to investigate precise laser cutting of sheets of 6061-T6 aluminum alloy, which are notable for their heat conductivity and light reflection [8]. Using analysis of variance (ANOVA) and design of experiments (DoE), the impacts of process factors on the kerf geometry and R_a were examined.

At 700 mm/min, the laser can cut 1-mm-thick sheets of AA6061-T6 with minimal kerfs, a fine taper angle, a low dross height, and R_a, of around 4 μm. When cutting stainless steel, Shinde et al. [9] studied effect of parameters for the LBM method on the kerf width and R_a. According to the findings, the assist gas pressure and laser power have the biggest impacts on the kerf width and R_a, respectively, whereas the cutting speed has a considerably lower impact. Using CO_2 laser machining, Khan et al. investigated the impact of the two key laser parameters, travel speed and

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power, on machinability, specifically kerf wall inclination, MRR, and R_a of Inconel 718 [10]. Increasing power with a slow travel speed have been observed to increase kerf wall inclination. Maximum MRR and minimal R_a were produced by low power and high travel speed. Samson et al. investigated the best way to operate the variables, such as gas pressure, cutting speed, and laser power, when working with Inconel-718 material [11]. Lopatková et al. studied the influence of laser beam power and weld joint shape on R_a. Machined on AW2099 aluminum-lithium alloy, the surface roughness varied from Ra 0.8 to Ra 15. To assess porosity, computer tomography was used, however surface roughness had a little effect on porosity and joint form [12]. Cagan et al. evaluated the influence of high-speed machining on the surface quality and on-chip formation of Al7075-T6 aluminium alloy. MQL conditions increased surface quality, however there was no significant difference in chip morphology or R_a across various cutting speeds [13]. Patel et al. examined the R_a in turning high-strength Al 7075 utilizing a central composite design (CCD). The analysis anticipated test scenarios with an error rate of fewer than 8.51 percent. Using principal component analysis and the JAYA method to optimize roughness and MRR yields an absolute deviation of 7.97 percent [14]. Dev et al. studied the influence of coating and polishing on the R_a of 24345WP aluminum alloy during dry machining. Experiments were done using 6 mm 2-flute end mill cutters on workpiece. By reducing chip tool friction, polished flute tools improve surface finish [15]. Struzikiewicz and Sioma examined surface quality difficulties after laser sintered AlSi10MG alloy powder. They developed guidelines for the machining of laser-sintering-produced objects [16].

Due to their great strength and low weight, titanium alloys are vital in the aerospace and medical sectors. Using laser-assisted machining considerably improved surface integrity indicators in Ti-6Al-4V superalloy machining, under regulated conditions [17]. Using the Taguchi method, researchers investigated the impact of parameters on LBM for drilling holes in titanium alloy. Reduced peak power has a substantial impact on machinability [18]. Sroka et al. studied the influence of laser treatment on the microstructure and mechanical characteristics of the surface layer of boron carbide-alloyed Al-Mg foundry alloy (B4C). They explored the relationship between laser alloying settings and the characteristics of the produced layer. Microstructural investigation was performed, and the tribological characteristics were obtained by alloying B4C powder with Ar at 0.5 bar under protected conditions [19]. Aluminum alloy is a lightweight, high-specific-strength, and fracture-resistant material that is used in the aerospace, rail transportation, and automotive sectors. Laser-arc additive manufacturing (LAAM) provides stable forming and fewer flaws, giving it a potential benefit for additive manufacturing of aluminum alloys. Miaoran investigated the tensile characteristics of thin-walled aluminum alloys manufactured utilizing arc and LAAM. Hybrid additive manufacturing decreased the size of the heat affected zone and increased the amount of -Al, Al-Si, and Al-Sr phases. The micro hardness, tensile strength, and elongation of the material all also increased [20]. In the medical, nuclear, and other sectors, new materials such as nickel alloys, titanium, and high-strength steels are employed extensively. Traditional machining techniques are hampered by issues such as limited tool life, poor surface quality, and lengthy machining periods. Researchers are investigating novel machining processes, such as thermal-assisted machining and LAM, to enhance productivity and surface integrity. Khatir et al. investigated the impact of cutting and heating factors on R_a in laser-assisted turning (LAT) procedures of 560 HV-hardened AISI 4340 hard steel [21]. Ni et al. examined the influence of laser scanning procedures and machining surfaces on the milling performance of selective laser melted Ti6Al4V alloy. High anisotropy is seen in cutting force, surface shape, and surface roughness, with microstructure and mechanical characteristics dominating. High cutting speed enhanced the machining of anisotropic characteristics. The chip form is conical spiral, and its degree of bending and length are greater than those generated by annealed Ti6Al4V alloy [22].

Because of its strength, corrosion resistance, tensile strength, and oxidation resistance, aluminum alloy is extensively utilized in the electronics, armament, aviation, and aerospace

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sectors. It is vital to eliminate cutting fluid and make it sustainable and environmentally benign, since micro-cutting has become a standard method for producing micro-parts. The research by Sun et al. intends to create micro textures on the back surface of sub-1 mm-diameter helical micro end mills. Experiments on dry micro-cutting revealed decreased R_a and tool wear. Micro textures not only increase the uniformity of the machined surface, but they also minimize tool wear on Al 6061 micro helical end mills [23]. Because of its excellent strength-to-weight ratio, aluminum-silicon alloys are frequently employed in technical applications including vehicles, ships, and airplanes. Turning is essential for making components with precise dimensions. Dhanalakshmi and Rameshbabu examined the optimization of turning parameters for LM 25 aluminum alloy in wet and dry settings. Taguchi's L9 orthogonal array was used, and Grey Relational Analysis was applied to improve the parameters [24]. Hofele et al. analyzed the process of laser polishing aluminum components that were fabricated by powder bed fusion using a solid-state disc laser with a power output of 4 kW, a multi-axis system, and a one-dimensional scanning optic [25]. Laser welding is an effective way for achieving weight reduction, and aluminum alloy is a good material for use in light weighting aircraft and new energy automobile applications. Nevertheless, flaws such as porosities and fractures might result in subpar mechanical performance and a shortened lifespan in service. The influence of single-beam and dual-beam laser lap welding on the microstructure, fractures, and mechanical characteristics of the material were examined by Chen et al. According to the findings, dual laser beam lap welding was superior than single laser beam welding, leading to improved welding flexibility and fewer fractures [26]. The method of laser cutting aluminum alloy sheet is investigated by Cavusoglu, with particular attention paid to laser power and cutting speed. The creation of heat-affected zones as well as surface morphology were also investigated, and hardness measurements were taken. According to the findings, the ideal cutting settings are 2600 W and 5 m/min, which results in cutting of the greatest possible quality [27]. A laser powder bed fusion procedure was used in order to carry out the structural and mechanical evaluations of an aluminum alloy with the composition AlSi10Mg. The study using X-ray diffraction showed both fine grain and coarse grain areas. When the laser power was increased, the microstructure became finer, but when the scan speed was slowed down, the microstructure became coarser. In order to investigate the mechanical qualities, experiments including relative density, micro hardness, and surface roughness were carried out by researchers [28].

Milling tools that have been micro-structured may considerably increase machining performance by lowering the amount of force and vibration required. Linear grooves (LG) and V-shaped grooves (VG) were examined as two distinct kinds of grooves that may be found on the tool rake face by Pan et al. In comparison to other types of milling tools, the VG milling tool worked superiorly, as shown by the findings, which demonstrated a decreased average milling load and a root mean square error of 6.94%. In addition, the VG milling tool was successful in achieving reduced galling wear and scratch marks, which led to the lowest surface roughness possible of 0.541 [29]. Milling a sheet of 2024 aluminum alloy that was 2 millimeters thick required the employment of a Q-switched fibre laser with 30 watts of power. Several different factors were used in the machining process to create square pockets. After measuring the attained depth and roughness, MRR was computed. ANOVA and RSM were used in order to simulate the behaviors of the process, and Multi-Response Optimization (MRO) methodology was utilized in order to determine the circumstances under which the process may run at its most efficient by Leone et al [30]. Due to their low density and strong resistance to corrosion, light metal alloys such as aluminum are seeing an increased amount of application in the automobile sector. Their poor mechanical qualities, on the other hand, restrict the applications for which they may be used, which need great surface hardness and resistance to wear. In the last 20 years, laser processing has made tremendous strides in improving surface treatment by introducing a variety of alloying materials, as well as increasing hardness and abrasion resistance. As a consequence of this body

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of work, the surface layer of aluminum was altered by the introduction of a combination of titanium and iron particles, which led to a considerable improvement in the material's mechanical characteristics [31].

Work-hardened alloys run the risk of suffering a loss in strength in heat-affected zones, while precipitation-hardened alloys either coarsen or dissolve when subjected to the same conditions. Because of its high heat conductivity and reflectivity, aluminum has a lower laser beam absorptivity, which in turn results in less efficient processing. Because of its low melting temperature and high density, it often results in weld flaws such as porosity, humping, and under fills. New laser systems, welding consumables, procedures, and approaches will be required for any future improvements in laser welding of aluminium alloys [32]. Based on the findings of the study by Bhaduri et al., a new technique for laser polishing aluminum alloys is proposed. This method results in a considerable improvement in the remelting of the material, with a reduction of 80-88% in the average roughness and residual stresses. However, bulk hardness was reduced by 15-20% due to the use of laser polishing in comparison to unpolished SLM components. When working with thermally conductive materials, maintaining the appropriate surface integrity attributes requires careful management of the heat dissipation process [33]. The AA7068 aluminum alloy materials are put through their paces utilizing laser welding, a technique that is known for its speed and effectiveness in the aircraft manufacturing and military service sectors. When trying to optimize the parameters for laser welding, there are four aspects that are taken into consideration: transverse speed, laser power, wire supply rate, and wire size. The ideal tensile strength is determined by the use of Taguchi design trials, and Minitab 18 is used to do the factor manipulations by Sathish et al. [34].

EXPERIMENTAL PLAN

The significance of surface roughness cannot be overstated, as it directly impacts both the functionality and visual appeal of machined components. Laser Beam Machining (LBM) has emerged as a prominent technique renowned for its precision and adaptability. This investigation delves into a meticulous examination of surface roughness (Ra) concerning the application of LBM on aluminium alloy. The experimental framework is intricately crafted to decipher the nuanced connections between various process parameters and surface roughness outcomes. By undertaking this systematic exploration, we aim to unravel the intricacies of the LBM process and its effects on aluminium alloy, ultimately contributing to the refinement of machining practices for improved and consistent surface finishes. This study holds promise in advancing our understanding of LBM's impact on aluminium alloy surfaces and fostering advancements in the manufacturing sector.

Material Selection and Characterization

In the preliminary stages of our experimental investigation on the surface roughness of laser beam machining of aluminum alloy, a meticulous approach is adopted, beginning with the judicious selection of the aluminum alloy material. This crucial decision is informed by a comprehensive evaluation of the mechanical characteristics inherent to the chosen material. Understanding and documenting the baseline mechanical properties are imperative, serving as a foundational reference for the subsequent analytical phases of our study. By thoroughly characterizing the mechanical attributes of the selected aluminum alloy, we aim to establish a clear understanding of its inherent properties. This preliminary step is vital in ensuring that the forthcoming experimental outcomes are not only accurate but also specific to the chosen alloy. The specificity of the material selection enhances the reliability and relevance of our study, as it enables us to draw precise conclusions about the impact of laser beam machining on the surface roughness of the identified aluminum alloy. In essence, this methodical initiation lays the groundwork for a robust and meaningful exploration into the intricate dynamics of laser beam machining and its effects on the surface quality of aluminum alloys.

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Laser Beam Machining System

A cutting-edge experimental investigation delves into the intricacies of surface roughness in laser beam machining of aluminium alloy. The focal point of this research is the utilization of the state-of-the-art AMADA LCG3015AJ laser beam machining system, boasting a formidable 6000W fibre laser. This advanced machinery serves as the cornerstone for conducting precise and meticulous experiments, offering unparalleled control over a myriad of process parameters. The AMADA LCG3015AJ system is chosen deliberately, embodying a commitment to employing cutting-edge technology in the pursuit of scientific excellence. Its capabilities extend beyond conventional machining systems, providing researchers with a unique opportunity to explore the nuanced effects of various process parameters on the resultant surface roughness. The 6000W fibre laser, a technological marvel in itself, ensures high energy density and precision in material removal during the machining process. This experimental endeavor aims to unravel the intricate relationship between process parameters and surface roughness in aluminium alloy machining. The utilization of the AMADA system elevates the study, promising accurate and repeatable experimental conditions that are essential for drawing meaningful conclusions and contributing to the continuous evolution of laser beam machining techniques.

Factorial Design Matrix

Manufacturing and materials processing, the surface roughness of machined components plays a pivotal role in determining the overall quality and functionality of the final product. This experimental investigation delves into the intricacies of surface roughness in the context of laser beam machining applied to aluminium alloy. To systematically unravel the complexities surrounding this machining process, a factorial design matrix is strategically employed. The selection of factors for this experimental matrix is grounded in a comprehensive review of existing literature, drawing attention to key variables that exert significant influence on the outcome of laser beam machining. Parameters such as laser power, scanning speed, and focal length emerge as critical elements, each known to impact surface roughness in distinct ways. By incorporating these factors into the design matrix, a wide array of parameter combinations is covered, facilitating the acquisition of exhaustive data. This meticulous approach ensures that the ensuing analysis is not only robust but also capable of providing nuanced insights into the interplay of variables affecting surface roughness. Through this experimental investigation, we aim to contribute valuable knowledge to the optimization of laser beam machining processes for aluminium alloy, ultimately enhancing the precision and quality of machined components.

Response Surface Methodology (RSM)

In delving into the intricacies of laser beam machining on aluminium alloy, our experimental investigation revolves around the systematic application of Response Surface Methodology (RSM). At the core of our methodological approach lies the Box-Behnken design (BBD), a statistical tool chosen for its remarkable efficiency in pinpointing optimal process parameters. By strategically manipulating the input variables, such as laser power, scanning speed, and focal length, we aim to unravel the complex interplay between these factors and the resultant surface roughness. Response Surface Methodology empowers us to construct a robust mathematical model that encapsulates the intricate relationship between these influential input parameters and the desired output—surface roughness. This modeling not only facilitates a comprehensive understanding of the underlying dynamics but also serves as a predictive tool. The derived model equips us to forecast the optimal conditions necessary to achieve the desired surface finish. As we embark on this experimental journey, the amalgamation of RSM and BBD promises to unravel nuanced insights into laser beam machining of aluminium alloy, paving the way for enhanced precision and efficiency in metal processing.

Experimental Setup and Parameters

In the pursuit of advancing manufacturing processes, an experimental investigation was conducted at M/s Anand Lasers in Pune, India, focusing on the surface roughness of laser beam

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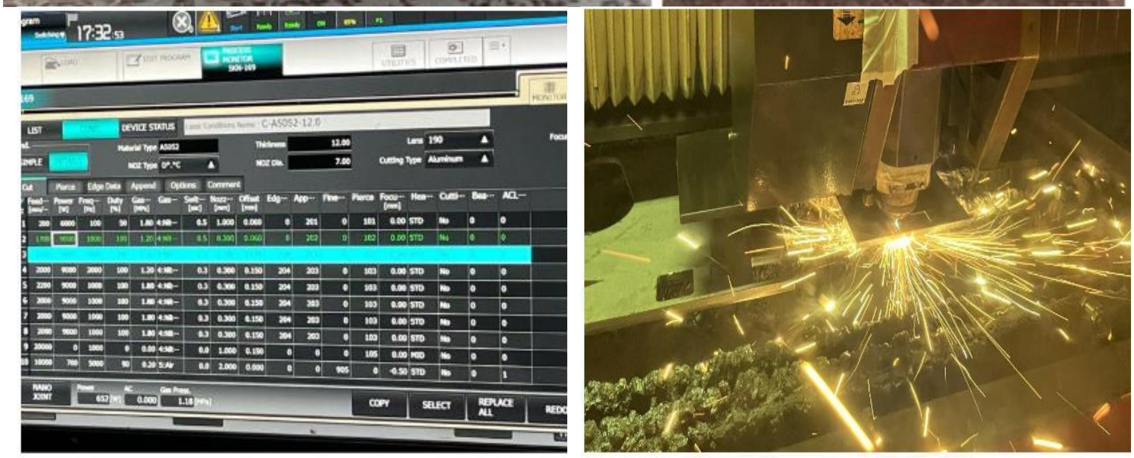
machining applied to aluminum alloy, specifically Al 6061. The chosen material had a thickness of 8 mm, with dimensions measuring 250 mm × 220 mm × 8 mm. Nitrogen was employed as the assist gas during the laser machining process, a critical parameter influencing the overall outcome. To provide a visual insight into the experimentation, Figure 5. presents samples of the 8mm cut pieces and the raw material itself. These samples serve as tangible evidence of the machining precision achieved during the experimental phase. Additionally, the composition and pertinent details of Al 6061 are meticulously outlined in Table 2, shedding light on the alloy's inherent characteristics. The experimental setup and methodology at M/s Anand Lasers aimed to comprehensively explore the effects of laser beam machining on the surface roughness of Al 6061. As surface quality plays a pivotal role in the performance of machined components, this investigation holds significance in enhancing our understanding of the intricate interplay between laser parameters and resultant surface characteristics in the context of aluminum alloy machining.



Control Panel on the CO_2 LBM

Cutting of Aluminum Alloy Al [6061] and MITUTOYO SJ-210

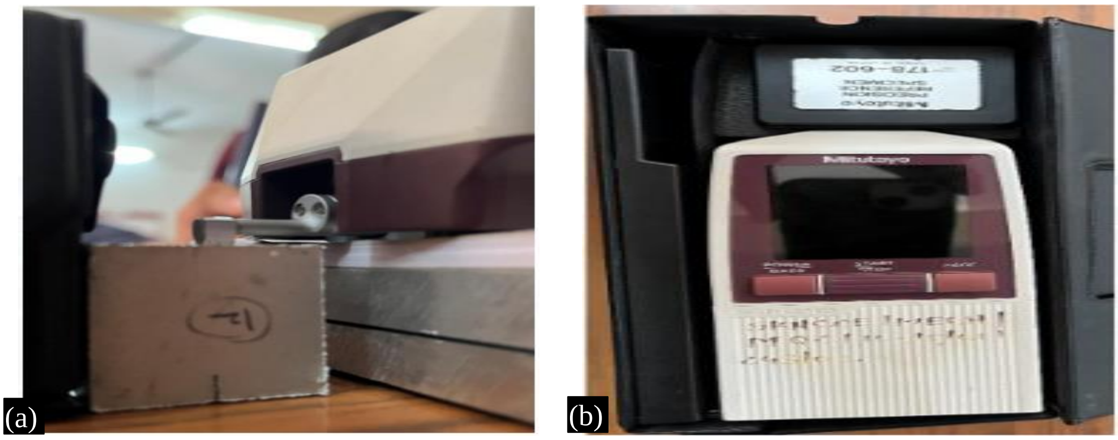


Figure 5. Samples of 8mm (a) Cut Pieces; (b) Material.

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A number of factors greatly affect the effectiveness and caliber of the cutting or machining process in laser beam machining (LBM). These parameters are divided into three categories: process, material, and laser parameters like, Laser Power, Gas pressure and cutting speed.

Process Parameters and Ranges

Laser beam machining, the experimental investigation on the surface roughness of aluminum alloy, specifically Al 6061, holds significant importance. Table 3 serves as a valuable reference, presenting a thorough compilation of laser beam machining process parameters and their corresponding ranges tailored for Al 6061. Among the key parameters outlined in the table are laser power, cutting speed, and assist gas pressure. These factors are not mere technicalities; instead, they wield substantial influence over the ultimate surface roughness of the machined aluminum alloy components. The meticulous selection of these machining parameters emerges as a critical determinant, shaping the outcome of the experimental investigation. Laser power, with its capacity to influence material removal and heat generation, stands as a cornerstone parameter. Similarly, cutting speed plays a vital role in determining the efficiency of the machining process, impacting the overall quality of the machined surface. The assist gas pressure, on the other hand, contributes to the removal of molten material and helps in achieving desired surface characteristics. As this experimental exploration unfolds, the intricate interplay of these parameters will be unveiled, shedding light on the nuanced relationship between laser beam machining conditions and the resultant surface roughness of Al 6061.

Table 3. Levels of Process Parameters for LBM

Process Parameter	Min	Max
Laser power (watt)	5500	6000
Cutting speed (mm/min)	1300	1700
Gas pressure (MPa)	1.4	1.8

A number of variables, such as the kind of laser, the material to be machined, its thickness, and the particulars of the machining procedure, affect the tolerances that can be achieved throughout laser beam machining (LBM). Laser cutting typically has dimensional tolerances between ±0.025 mm and ±0.25 mm. Tolerances as small as ±0.025 mm can be reached in high-precision applications, particularly when using thin materials and well-optimized procedures.

Experimental Runs and Metrology Methods

Materials processing, particularly in the domain of aluminum alloy machining, an experimental investigation delving into the intricacies of laser beam machining has been undertaken. The primary focus lies in scrutinizing the surface roughness of the machined aluminum alloy samples. The experimentation involves the systematic alteration of various machining parameters, such as laser power, scanning speed, and beam diameter, creating a matrix of diverse conditions. With each meticulously executed experimental run, aluminum alloy specimens undergo the laser machining process based on the predefined parameter combinations. A critical facet of this investigation is the precise evaluation of surface roughness (Ra), a key indicator of the quality and texture of the machined surface. To ensure accuracy and reproducibility, sophisticated metrology methods are employed during the assessment phase. These may encompass the utilization of advanced tools such as profilometers or state-of-the-art 3D optical scanners. These metrology methods play a pivotal role in capturing the nuanced details of the surface topography, providing a comprehensive understanding of how variations in laser machining parameters impact the resultant surface roughness. The utilization of such advanced measurement techniques ensures that the acquired data is not only precise but also reliable, laying the foundation for a thorough analysis of the intricate interplay between machining parameters and surface quality in the realm of laser beam machining of aluminum alloy.

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Statistical Analysis

Advanced manufacturing processes, laser beam machining of aluminum alloy stands out as a promising technique. To delve into the intricacies of this method, an experimental investigation was undertaken with a keen focus on surface roughness. The primary objective of this study is to unravel the intricate relationships between the chosen process parameters and the resultant surface roughness. A crucial aspect of this investigation involves the rigorous collection of experimental data, meticulously documenting the outcomes of varying process conditions. Subsequently, the amassed data undergoes a comprehensive statistical analysis, utilizing sophisticated tools and techniques. This analytical approach is paramount in discerning patterns, trends, and correlations that may exist within the dataset. The utilization of statistical tools not only aids in the identification of influential factors affecting surface roughness but also facilitates a deeper understanding of the intricate interplay between various machining parameters. Through this experimental exploration, the study aspires to contribute meaningful insights to the field, shedding light on the nuanced dynamics that govern the surface finish in laser beam machining of aluminum alloys. This research endeavor is poised to advance our knowledge in precision manufacturing and pave the way for optimizing the machining processes for enhanced surface quality in aluminum alloy components.

Eight-millimeter cut pieces obtained through laser beam machining of aluminum alloy showcase varying surface roughness characteristics. The experimental investigation explores the influence of machining parameters on the quality of the cut pieces. The material under examination is aluminum alloy, chosen for its significance in industrial applications and the growing utilization of laser beam machining for precision and efficiency in metal fabrication processes.

Table 4. Experimental plan for LBM of Al 6061 material.

		Factor 1	**Factor 2**	**Factor 3**
Std.	***Run***	***A: Laser power (watt)***	***B: Cutting speed (mm/min)***	***C: Gas pressure (MPa)***
7	1	5500	1500	1.8
17	2	5750	1500	1.6
16	3	5750	1500	1.6
5	4	5500	1500	1.4
8	5	6000	1500	1.8
4	6	6000	1700	1.6
2	7	6000	1300	1.6
14	8	5750	1500	1.6
3	9	5500	1700	1.6
13	10	5750	1500	1.6
1	11	5500	1300	1.6
12	12	5750	1700	1.8
15	13	5750	1500	1.6
11	14	5750	1300	1.8
10	15	5750	1700	1.4
9	16	5750	1300	1.4
6	17	6000	1500	1.4

RESULTS AND DISCUSSION

In this section, we delve into a comprehensive analysis of the experimental investigation conducted on the surface roughness of aluminum alloy during laser beam machining. The primary focus is on understanding the intricate relationships between various process parameters and the resultant surface roughness values. The exploration begins with a meticulous review of the

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experimental data, shedding light on the diverse surface roughness outcomes observed under different combinations of process parameters. Graphical representations, particularly contour plots, play a pivotal role in elucidating the correlations between the laser beam machining process parameters and the corresponding surface roughness. These visual aids serve as valuable tools in discerning trends, patterns, and uncovering noteworthy discoveries within the dataset. The ensuing discussion navigates through the interpretation of the acquired data, emphasizing recognized trends and bringing attention to any distinctive patterns that emerged during the experimentation. A profound investigation is conducted to analyze the influence of specific process factors on the surface roughness of the machined aluminum alloy. By scrutinizing the experimental results, the section aims to pinpoint the ideal parameter ranges that yield optimal surface finishes. This exploration not only contributes to enhancing the understanding of the laser beam machining process but also provides practical insights for achieving desired surface qualities.

To validate the robustness of the acquired data, a comparative analysis is conducted with existing theoretical models and empirical relationships sourced from relevant literature. This step ensures the accuracy and dependability of the experimental results, aligning them with established knowledge in the field. The experimental setup involves a series of meticulously planned experiments conducted on 17 samples. These samples, created using a laser cutter, consist of square blocks with dimensions measuring 30 mm × 30 mm. The experimental data, crucial for understanding the nuances of surface roughness, is compiled and presented in Table 5, detailing the variations observed in surface roughness for a material thickness of 8 mm. This systematic approach to experimentation sets the stage for a robust and thorough investigation into the surface roughness of aluminum alloy during laser beam machining.

Table 5. Experimental Data of Surface Roughness for Material of Thickness 8 mm

Std.	**Run**	**Factor 1**	**Factor 2**	**Factor 3**	**Response 1**
		A: Laser power (watt)	***B: Cutting speed (mm/min)***	***C: Gas pressure (MPa)***	***Surface Roughness (micron)***
7	1	5500	1500	1.8	1.665
17	2	5750	1500	1.6	1.585
16	3	5750	1500	1.6	1.525
5	4	5500	1500	1.4	1.463
8	5	6000	1500	1.8	2.041
4	6	6000	1700	1.6	2.4
2	7	6000	1300	1.6	1.328
14	8	5750	1500	1.6	1.394
3	9	5500	1700	1.6	2.052
13	10	5750	1500	1.6	1.439
1	11	5500	1300	1.6	1.112
12	12	5750	1700	1.8	1.964
15	13	5750	1500	1.6	1.405
11	14	5750	1300	1.8	1.226
10	15	5750	1700	1.4	1.761
9	16	5750	1300	1.4	1.129
6	17	6000	1500	1.4	2.092

The surface roughness values that laser cutting produces for metals like aluminum alloy can vary from about 1.0 to 10.0 micrometers.

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Statistical Analysis

manufacturing and materials processing, the surface quality of machined components plays a pivotal role in determining the overall performance and functionality of the final product. An experimental investigation on the surface roughness of laser beam machining of aluminum alloy has been conducted, employing statistical analysis to unravel the intricate relationship between various process factors and the resultant surface roughness. The study utilized a well-designed experimental setup, encompassing multiple experiments to systematically assess the impact of process factors on surface roughness. The statistical tool of analysis of variance (ANOVA) was employed to scrutinize the models created for different output parameters. The focus of this discussion centers on the ANOVA results for surface roughness, which provides valuable insights into the significance of various factors influencing the machining process. The obtained ANOVA results, as presented in Table 6, unveil a statistically significant model with an F-value of 15.69. This F-value is notably high, indicating that the model is not likely attributed to random noise, with only a 0.07 percent chance of such an occurrence. The P-values associated with the model terms further confirm their significance, with values ≤ 0.0500, underscoring the impact of these terms on surface roughness.

Among the primary model terms, A, B, and A^2 stand out as significant contributors to surface roughness. The corresponding F-values and P-values for these terms highlight their substantial impact on the machining process. Conversely, terms like C, AB, AC, BC, B^2, and C^2 exhibit higher P-values, exceeding the 0.1000 threshold, indicating their negligible influence on surface roughness in this context. The lack of fit F-value of 3.85 suggests that any lack of fit is minor compared to pure error. This is reinforced by the associated P-value of 0.1128, signifying that there is an 11.28 percent probability that the lack of fit F-value is due to noise. Consequently, the lack of fit is deemed not significant, affirming the reliability of the model in explaining the variations in surface roughness. The detailed breakdown of the ANOVA results sheds light on the individual contributions of each factor and their interactions. Notably, factors A and B, along with their quadratic forms (A^2 and B^2), emerge as key determinants of surface roughness. These findings provide valuable guidance for optimizing the laser beam machining process for aluminum alloy to achieve desired surface quality.

Table 6. ANOVA for Surface Roughness.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.13	9	0.2371	15.69	0.0007	significant
A	0.3077	1	0.3077	20.36	0.0028	
B	1.43	1	1.43	94.58	< 0.0001	
C	0.0254	1	0.0254	1.68	0.2358	
AB	0.0044	1	0.0044	0.2882	0.6080	
AC	0.0160	1	0.0160	1.06	0.3378	
BC	0.0028	1	0.0028	0.1858	0.6794	
A^2	0.3169	1	0.3169	20.96	0.0025	
B^2	0.0018	1	0.0018	0.1220	0.7372	
C^2	0.0214	1	0.0214	1.42	0.2727	
Residual	0.1058	7	0.0151			
Lack of Fit	0.0786	3	0.0262	3.85	0.1128	not significant
Pure Error	0.0272	4	0.0068			
Cor Total	2.24	16				

The experimental investigation coupled with statistical analysis has unraveled the intricate dynamics governing the surface roughness in laser beam machining of aluminum alloy. The insights derived from the ANOVA results pave the way for informed decision-making in process optimization, ultimately enhancing the surface quality of machined components in the realm of advanced manufacturing.

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Final Expression Using Coded Factors

In the culmination of our experimental investigation on the surface roughness of laser beam machining of aluminum alloy, the final expression incorporating coded factors has been derived. The formulated equation is represented as follows:

$$\text{Surface Roughness} = +1.47 + 0.1961A + 0.4228B + 0.0564C + 0.0330AB - 0.0633AC + 0.0265BC + 0.2743A^2 - 0.0209B^2 + 0.0713\,C^2$$

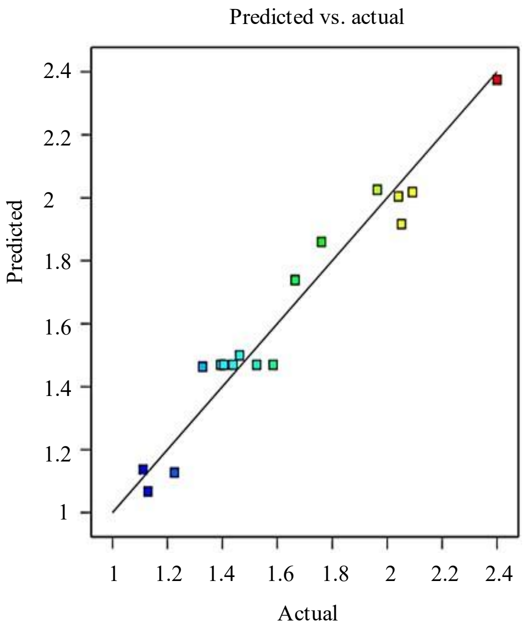

Figure 6. Predicted vs actual surface roughness values.

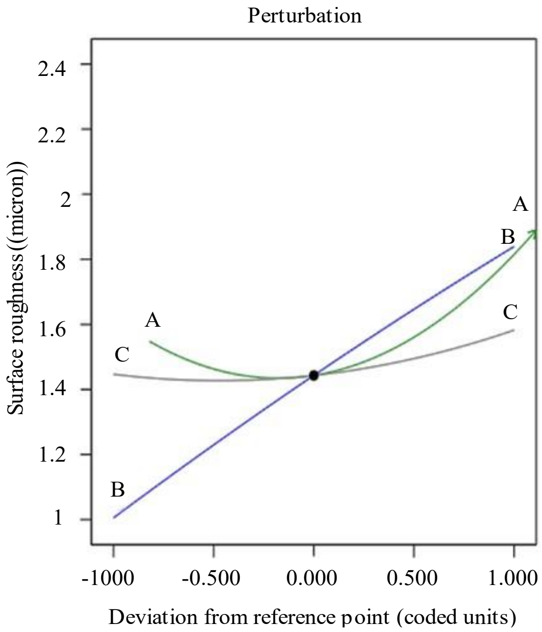

Figure 7. Perturbation plot for Surface Roughness

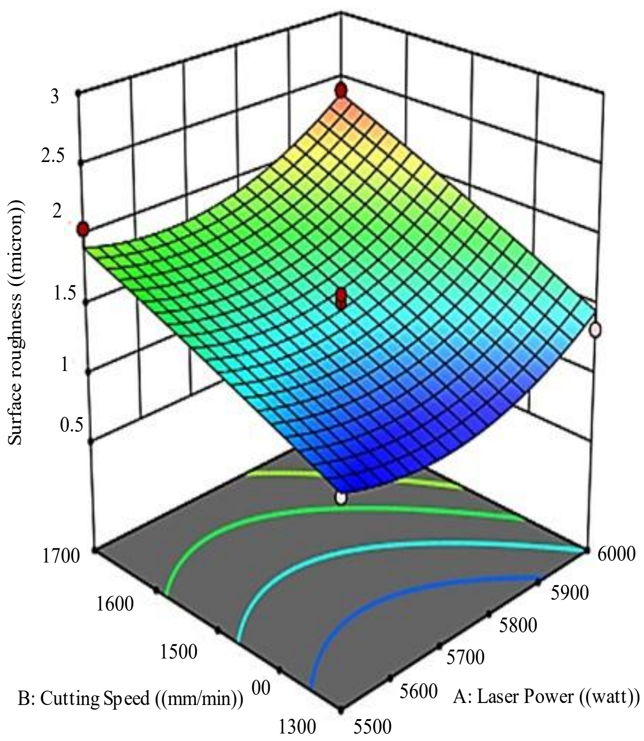

Figure 8. 3D plot of performance parameters on surface roughness.

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This expression elucidates the relationship between surface roughness and the various factors under consideration, namely laser power (A), scanning speed (B), and pulse frequency (C). The coefficients signify the impact and magnitude of each factor on the surface roughness, aiding in the optimization of machining parameters. Figure 6. visually captures the correlation between the actual outcomes of the experiments and the values predicted by the model. The congruence between expected and experimental results attests to the adequacy of the constructed model. Furthermore, Figure 7. provides insight into the nuanced behavior of surface roughness concerning laser power, demonstrating an initial decrease followed by an increase, potentially attributed to the evolving nature of material melting under varying power levels. To enhance comprehension, Figure 8. presents a 3D plot illustrating the combined influence of the performance factors on surface roughness. This comprehensive visualization aids researchers and practitioners in gaining a holistic understanding of the intricate dynamics governing the laser beam machining process for aluminum alloy, facilitating informed decision-making in pursuit of optimal surface quality.

CONCLUSION

The experimental investigation on the surface roughness of laser beam machining of aluminum alloy, specifically Al 6061, has provided valuable insights into the intricate dynamics governing the machining process. The research utilized the advanced AMADA LCG3015AJ laser beam machining system with a 6000W fibre laser, ensuring precise control over critical process parameters. The factorial design matrix and Response Surface Methodology (RSM) were systematically employed to explore the nuanced relationships between laser power, cutting speed, gas pressure, and surface roughness. The experimental runs, conducted at M/s Anand Lasers in Pune, India, involved the systematic alteration of process parameters, leading to the creation of 17 samples. Statistical analysis, particularly ANOVA, revealed a statistically significant model with laser power (A), cutting speed (B), and their quadratic forms (A^2 and B^2) emerging as key determinants of surface roughness. The lack of fit was deemed not significant, affirming the reliability of the model in explaining variations in surface roughness. The final expression, incorporating coded factors, provides a quantitative understanding of the relationship between surface roughness and laser power, cutting speed, and gas pressure. The predicted vs actual values, perturbation plot, and 3D plot visually capture the congruence between the experimental outcomes and the model predictions, validating the adequacy of the constructed model. This comprehensive investigation contributes to the optimization of laser beam machining processes for aluminum alloy, enhancing the precision and efficiency of metal fabrication. The refined understanding of the intricate interplay between process parameters and surface roughness is pivotal for advancing the field of precision manufacturing and holds promise for practical applications in industries relying on aluminum alloy components.

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