Sustainable Surface Engineering Techniques: Evaluating the Environmental Footprint of Laser and Electron Beam Methods

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Abstract. This study provides an extensive overview of the latest developments in metal surface engineering, including methodologies, characterizations, and applications. The study highlights how important surface engineering is for improving metallic materials' functionality and performance across a range of sectors. Therefore, a series of techniques are presented in this paper for evaluating design surfaces' mechanical properties, topological properties, and microstructure. This paper presents a review of current advances in the field, focusing on functionalized surfaces for energy applications, nanostructured coatings for corrosion protection, and biomedical applications of modified surfaces. Since lasers and electron beams are mechanically and tribologically superior, there is a long discussion about their environmental footprint. A special focus in the study is on surface functionalization, nanostructured coatings, corrosion protection, and biological applications, as well as recent developments in the field. The paper also discusses the impact they have on the environment. Surface engineering approaches have long been known to enhance corrosion protection, wear resistance, and component functionality in aerospace, automotive, electronics, and healthcare sectors. Thus, the paper's conclusion emphasizes that more research and development are needed to overcome constraints and take advantage of emerging trends in surface engineering in order to overcome constraints and take advantage of new trends. The paper provides a solid foundation for future research and development in a range of industries affected by surface engineering.

Keyword. Electron Beam Melting; Selective Laser Melting; Microstructure, Sustainability, Environmental Impact.

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1 Introduction

Metallic materials are used in a wide range of industries, so surface engineering is an important area of study for improving their performance. By changing its surface properties, metal surfaces can be made stronger, more wear-resistant, corrosion-resistant, and more biocompatible. New applications and dramatic outcomes have been reported as a result of recent advancements in surface engineering approaches and characterisation technologies [1]. By using heat or energy, PVD, CVD, and laser surface treatment modify the material by using physical vapor deposition (PVD). The adhesion, hardness, and surface roughness of the surfaces can easily be modified [2]. Nonetheless, chemical methods such as chemical etching, sol-gel coatings, electroplating, and electroless plating offer a chance to manipulate and deposition surfaces, as well as corrosion resistance and biocompatibility. This development is very promising as it provides a solution to corrosion-related malfunctions that can have deadly consequences in areas such as marine, aerospace, and automobile industries. Moreover, surface technologies have made important contributions to the field of biomedicine in recent years. Dental prosthetics and orthopedic implants can benefit from bioactive coverings because it promotes the integration of titanium into the bone, thus reducing the chances that these implants will reject [17-18]. Moreover, antimicrobial medications for surfaces are being developed to prevent infections in hospital environments and provide a strong barrier against the growth of bacteria on materials and surgical instruments [19].

Surface technology advancements have also had an impact on the energy industry. Surface alterations these have been used to materials that exhibit high efficiency in energy conversion to enhance their catalytic activity. Furthermore, research has focused on surface functionalization and coatings to increase the longevity [20, 21]. Surface engineering methods are used in the aerospace and military industries to improve the functioning and resilience of essential components that are exposed to harsh conditions [22].

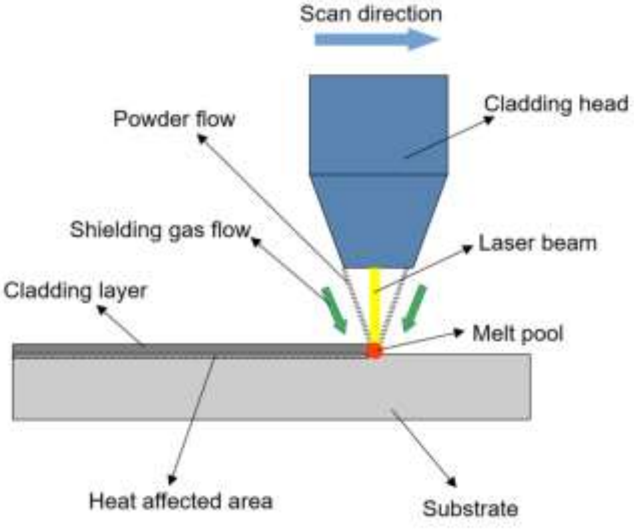

Fig. 1: Surface engineering techniques [6].

The automotive industry's use of corrosion prevention technology and wear-resistant coatings is crucial to the reliability and safety of car parts and engine components [23–24]. Conversely, surface modifications make it possible to produce electrical and semiconductor devices with great performance. Through its assistance in assessing the efficacy of coatings and surface treatments, researchers and engineers may improve material performance and streamline operations. In sectors where exact control over surface characteristics is critical, such semiconductor manufacturing, automotive, aerospace, and microelectronics, surface profilometry is vital. ‘Table 1 presents a comparison of the various characterisation techniques covered previously.

Table 1: Comparison of characterization methods in surface engineering.

Characterization Method & Citations	**Principle**	**Key Parameters Measured**	**Advantages**
Scanning Electron Microscopy (SEM)	Interaction of the scanning electron microscope beam with the material's surface	Surface composition, topography, and morphology	Wide field of vision and high-definition imagery
Transmission Electron Microscopy (TEM)	Electron beam passing through the sample	Microstructure, crystallography, defects, and interfaces	High-resolution atomic-scale analysis and imaging
X-ray Diffraction (XRD)	X-rays diffracted by the crystal plane lattice	Structure, phase confirmation, and crystal orientation	Accurate and non-destructive phase analysis Discovering the residual tension and texture
Atomic Force Microscopy (AFM)	Detecting the forces acting on the sample surface from a probe	Surface topography, roughness, and texture	Top-quality images and surface force measurements
Scanning Tunneling Microscopy (STM)	Tunneling flow between the surface of the material being studied and a sharp tip	Atomic-scale surface topography imaging	By using atomic-precision surface tracking for conductor and non-conductive substances to study the electrical structure and characteristics of surfaces
Surface Profilometry	Optical or mechanical measurement of surface profile	Surface roughness, step height, and feature dimensions	Rapid and non-invasive surface topography assessment

Using these characterisation approaches, researchers may completely understand the mechanical, topographic, and structural properties of surface-treated metals (Table 1)’. This data supports surface design technique evaluation, enhancement, and quality assurance. Additionally, by highlighting the relationships between processing parameters, microstructure, and functional attributes, the unique data collected by these methods will support the creation of surface engineering strategies and materials that are more successful. Which characterization procedures are best depending on the particular goals and specifications of the study on surface engineering?

2 Sustainability and Environmental Impact

Surface engineering is a fascinating field that intersects with sustainability in numerous ways. As a seasoned professional in materials and surface engineering, I’ve witnessed firsthand how advancements in this area can lead to more sustainable practices and products. Raw materials, completed commodities, and equipment movements were all investigated in the LCA research. The focus of this research was on reducing transport-related energy use and carbon dioxide emissions. As stated in a previous study [22], energy consumption, material use, and waste generation are important environmental impacts in the processing phase of L-PBF Ti-6Al-4V components.

Table 2: Summarization of literature review and their key findings.

Citations	Objectives	Description	Methodology
[12]	To evaluate L-PBF technology's sustainability by looking at how it uses materials, uses energy, and produces trash.	This goal is to evaluate the L-PBF technology's sustainability, taking into account waste production, energy usage, and material efficiency in the manufacturing process.	Experimental analysis, powder characterization
[13]	To determine the primary factors affecting the L-PBF Ti-6Al-4V components' long-term vitality and durability.	The primary goal of this purpose is to ascertain and comprehend the crucial elements that impact the sustainability of L-PBF Ti-6Al-4V components.	LCA methodology, data collection, impact assessment
[10]	To study how process variables affect the use of materials.	Optimizing material use and minimizing waste formation may be achieved by regulating laser power, scanning speed, and powder layer thickness.	Experimental analysis, statistical modelling
[14]	L-PBF	Comparing L-PBF to conventional production methods reveals lower environmental consequences, such as decreased emissions, material waste, and energy use.	Comparative LCA analysis
[13-14]	L-PBF process parameters	Enhancing laser power, scanning speed, and gate separation can lower the carbon footprint of L-PBF and increase energy efficiency.	Experimental analysis, energy measurements
[18-19]	Conduct LCA of LPBF Ti-6Al-4V parts	Comparing the sustainability of L-PBF Ti-6Al-4V components.	LCA methodology, data collection, impact assessment

A number of life cycle assessments (LCAs) have been performed on the energy use and emissions of greenhouse gas L-PBF technologies as shown above in table 2, which differ from traditional production methods. Additionally, this work carried out a more thorough investigation in the literature. The mechanism linking the mechanical characteristics into the process-induced porosity, internal stress residue, and the microstructure of Ti-6Al-4V alloy is explained, along with the basic distinctions between the three processes in terms of grain morphology, size, phase constituents, and texture. The literature claims that not many people completed such a methodical task.

3 Environmental Footprint of Laser and Electron Beam Methods

Modern industrial technology heavily relies on laser and electron beam welding, and new uses are always being discovered. These procedures produce a heat source that has features that are extremely desired for joints in many applications, especially those where production is very high, penetration is critical, and the degree of distortion after welding must stay low. Innovative design combinations for all buildings, including cellular structures that provide lightweight components, are made possible by additive manufacturing techniques. The electron beam's energy output is sufficient to melt a wide range of metals and alloys. Tool steel, cobalt-based super alloys, aluminum and its alloys, and other materials may be processed using EBT. Currently, the most extensively studied materials for EBT use are Ti alloys, such as Ti-6Al-4 V. Due to their superior properties, such as their higher mechanical strengths, low density, great resistance to corrosion, improved biocompatibility, and human allergic reaction, titanium alloys offer a wide range of potential uses. EBT offers a one-step manufacturing process for intricate structures like as porous, cellular, and mesh.

Using EBT, porous customized implants with exact porosity to match anatomical needs for medical use may be created. Additionally, the vacuum maintains a sterile and regulated environment while the hot process produces components with minimum residual stresses.

The capacity of EBT to generate a negative Poisson's ratio structure—also known as "auxetic behavior"—is another special quality. A negative Poisson's ratio is significant since it indicates that shear resistances will lead to increased fracture toughness. These ratios, which mostly rely on orientation, were found to range between 0.2 and 0.4.

One of the main benefits of EBT is faster production. A laser scans the surface point by point, greatly accelerating manufacturing. Additionally, an electron beam may heat the powder individually and concurrently at different locations. The powder is preheated, which reduces the requirement for supports and reinforcements during manufacture. However, the precision is reduced since the electron beam is somewhat broader than the laser beam at the powder level.

With other DMLF methods, the powder is applied directly to the sample using injection nozzles. Included in them are the Laser Engineered Net Shaping (LENS) method [23] and associated processes such as Direct Light Forming (DLF) and Direct Metal Deposition (DMD).

Electron Beam Melting (EBM) and Electron Beam Free Form manufacturing (EBF3) are two direct metal manufacturing techniques that use an electron beam [24].

One of the biggest benefits of applying additive manufacturing (AM) techniques in the medical field is the ability to create personalized implants just utilizing the disease-related data from Computer Tomography (CT) scans. While several additive manufacturing techniques can provide viable metallic implants, only "powder in bed" approaches can create the intricate, custom-designed scaffolds with regulated porosity required for bone tissue creation [25].

4 SLM and EBM Differences

This section discusses and highlights the distinctions between the SLM and EBM procedures. Using a precise Z-axis positioner, a layer of powder a few tens of microns thick is dispensed from the feed container onto the build platform in both procedures. The powder surface's X-Y plane is where the laser or electron beams work. The 3D computer model's programmed information, which is obtained from the examination of the sliced layers, regulates the distribution of powder. A positioner table is lowered after each layer of powder has melted, and another layer of powder is dispersed before being melted by the laser or electron beams. When a fully formed 3D element is produced, the procedure is over. The component is either taken straight off the construction platform after cooling or after heat treatment for stress alleviation [26].

The main parts that set these machines apart are the feed container, the deposition unit, the beam source, and the item assembly platform. SLM machines employ 50–200 W CO2 (10.6

µm) or Nd: YAG (1.06 µm) lasers. Utilizing a tungsten filament that has been heated, EBM machines generate an electron beam with a power of 50-3500 W. Temperature gradients during EBM operations are reduced by first preheating the sample with defocused electrons. A further option for SLM systems is preheating [27].

SLM machines employ an argon atmosphere to keep samples from oxidizing, however it is possible to carry out a procedure in a controlled environment to improve the manufactured material's mechanical qualities [28]. Unlike SLM machines, EBM machines function in a vacuum. The main reason for doing this is to stop energy from escaping before the beam reaches the component. The main process variables for all powder in bed techniques are the thickness of the layers that are formed, the speed and strategy of the scan, the gap between beam vectors (hatch spacing), and the beam power [29].

Unlike EBM in SLM manufacturing, the scanning speed may be adjusted based on two separate parameters: the exposure duration and the point distance [30]. The laser in SLM equipment operates in pulse mode rather than continuous focus. Consequently, the distance (the point distance) between two sites where the laser is focused and melting powder for a brief duration (the exposure time) determines the scanning speed [31].

5 Conclusion

There are a lot of similarities and distinctions between the welding procedures using laser and electron beams. They offer special benefits including minimal distortion and lightning-fast processing, but they can be quite expensive unless used in huge volume applications.

- From a scientific and technological perspective, the physical issues pertaining to beam source design, transmission, and concentration for electron beams have been resolved, while ongoing improvements are being made for high power lasers.
- When paired with a high degree of automation and CNC, laser and electron beam welding technologies are evolving into trustworthy, flexible, repeatable, high-quality production tools.
- Thus, these processes continue to be given top importance by the mass manufacturing, aerospace, energy, and heavy sectors. These procedures still need a significant amount of investment, but productivity gains may offset this, supporting their inclusion in the arsenal of industrial production instruments. Improvements in both technical and financial performance are the driving forces behind the development of laser and electron beam welding systems. Even if the two processes are rivals in certain areas, they are also highly complementary in others where they may coexist peacefully and advance industry.

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