A Systematic Review of Laser Surfacing, Resurfacing, and Cutting

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Abstract- Laser surfacing, resurfacing, and cutting are leading-edge laser machining processes that bring benefits not previously known to the machining industry through state-of-the-art techniques. Laser machining is growing rapidly as the industry adopts additive manufacturing, creating a need for a process review. This study aims to critique the viability of laser surfacing, rust removal, and cutting machine processes in industry. A comprehensive literature review approach was adopted on previous studies on laser machining processes. The study also mirrored the effects of laser machining operations parameters by determining how changing them affects the final product. The results confirmed that laser surfacing can enhance surface finish on both simple and complex geometries for various materials. It was also discovered that thermal expansion and pressure waves can remove unwanted particles such as rust and dirt in the case of laser cleaning. Laser cutting provides a thorough and precise cut with no tool wear. These methods can efficiently and precisely perform across various complex geometries with little waste and no tool wear. Additionally, results show that laser power and scanning speed parameters are the most important laser parameters used in determining the success of a laser machining operation. Hence, the authors emphasized the importance of carefully selecting laser parameters, ensuring they are specifically tailored to the material and condition of the workpiece. They also advocated further research to optimize parameter selection in laser machining processes.

Keywords: Laser surface finishing, laser cutting, laser rust removal, scanning speed, laser power, pulsing frequency, gas pressure

1. Introduction

Surface finishing, resurfacing, and cutting are machining operations widely used in the fabrication and upkeep of metal parts. These processes are effective for most cases and especially useful for simple geometry parts. Downsides of current methods include a lack of flexibility in part geometry, time required to treat, and the necessity to replace tooling due to wear [1].

Surface finishing is a very significant area in the manufacturing of products in industries where surface properties are critical to the functionality of the final product. It is one of the standard quality metrics for most mechanical components. In the aerospace, medical, automotive, and electronics industries, surface finish is critical to the functionality, aesthetics, mechanical properties, topographic quality, and accuracy of products that have very stringent tolerances for proper operation. Current techniques used in the industry to achieve these include milling, abrasive methods, and chemical processes.

Resurfacing, sometimes referred to as cleaning, refers to the removal of contaminants on the surface layer of a part (usually rust/oxidation). Hence, the method can be applied to small parts that are refurbished and reused or to enlarge steel structures to extend life of such structures. Current methods include sandblasting, grinding, and chemical sprays. Major downsides are labor intensity and environmental sustainability [2].

Cutting is the oldest and most established method of the three being discussed and can be applied to a plethora of applications. Cutting can take the form of a cutoff tool on a lathe, milling to remove material, rotating or reciprocal saws in wood and metal, and table machine operations for sheet metal. In this paper, attention also focuses on the area of table machine cutting operations. Current table machine methods include waterjet and plasma cutting. Research affirmed that the major downside of waterjet cutting is its relatively slow cutting speed. The downside of plasma cutting is its relative lack of precision and rough-cut quality [3].

1.1 Concept of Laser Surface Finishing

Laser surface finishing leverages the precision and high energy density of lasers to induce localized re-melting to polish or ablate surface asperities and create a finish that is within quality control standards of a final product without any mechanical interaction **(Fig. 1).** These two methods utilize distinct underlying physical mechanisms to achieve the same premise of superior surface finish. However, works of literature on re-melt polishing as a technique of interest for achieving laser surface finishing were reviewed extensively in this study.

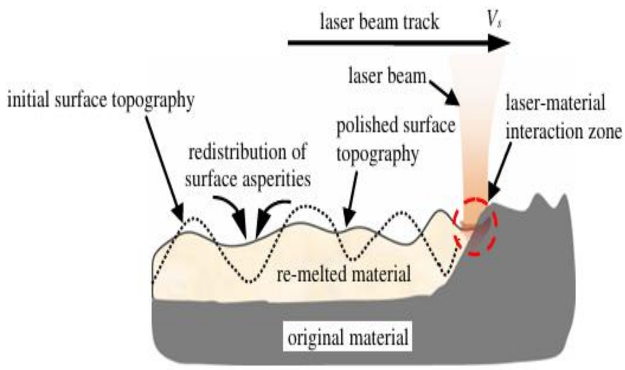

Fig. 1. Schematic of laser remelting mechanism [5]

Remelting is primarily governed by the nuanced physics of micro-melt pools created from laser energy deposition. B. Guan et al. [4] and Bordachev et al. [5] in their studies on the performance of laser polishing in finishing metallic surfaces. The studies elucidated the mechanism of a laser beam's operation. According to the study, the laser beams acting on the material surface have a near-Gaussian energy distribution, with central areas of effect hotter than the edges, inducing a temperature gradient in the area. The studies elucidated the mechanism of a laser beam's operation. According to the study, the laser beams acting on the material surface have a near-Gaussian energy distribution, with central areas of effect hotter than the edges, inducing a temperature gradient in the area. Based on the material reflectivity and absorption coefficient, the transient temperature field behaves according to the heat equation. When the melt temperature is reached, this flow of melted material is governed primarily by Marangoni convection, which drives cooler, more viscous, and more surface-tense liquid to flow towards hotter, less viscous, and surface-tense areas, inducing shear stresses in the fluid. This effect, combined with the principles of capillary pressures, induces normal stresses on the surface flow, driving flow from high areas of curvature, present on the convex surface peaks, to low areas of curvature on the surface valleys. Solidification typically occurs at cooling rates ranging from 10^3 to 10^6 K/s. The heat energy diffuses to the bulk material from the melt pool almost instantaneously because the immense temperature gradient is created, localized to the melt on the scale of only a few micrometers. This rapid solidification results in ultra-fine grain structures on these surfaces that are free of large crystallite growths, and are exceptionally harder than the underlying material, unaffected by the heat of polishing. This physical behavior, coupled with the thermal and fluid dynamical effects present, culminates in surfaces solidifying with smooth, homogenous topographies [4] and [5].

Laser remelting is advantageous over traditional surface finishing techniques in many ways for industrial applications. It is a non-contact, non-abrasive technique that essentially eliminates tool wear, contamination from consumables, and preserves underlying bulk material and its mechanical properties. Due to the inherent lack of tooling required, maintenance requirements and downtime can be minimized. Complex geometries, unlimited internal channels, and lattice structures are polished without a rigid mechanical fixture with a non-contact nature. Lasers can be mounted to CNCs or robotics and automated to treat the specific component being manufactured. The rapid heating and cooling inherent in the remelting process can create a surface layer that exhibits enhanced hardness, corrosion resistance, and mechanical wear resistance compared to surfaces left untreated during the manufacturing process. It applies to a wide array of metal alloys, ceramics, and glasses, provided parameterization is optimized for the desired laser-material interaction **(Fig. 2)**. Laser re-melting reduces environmental impacts by eliminating the need for hazardous corrosive chemicals and simplifying cleanups. Integration into additive manufacturing (AM) processes has an upside. Typically, these parts have surfaces that exhibit high roughness and unmelted particulates. By incorporating these methods into the manufacturing processes involved, manufacturing can be streamlined and potentially remove the errors present when relocating products to other facilities for treatment. The technologies of laser surface remelting present compelling upside to areas of manufacturing where high throughput, streamlined manufacturing, minimal material interaction, material versatility, and sustainability are paramount [5].

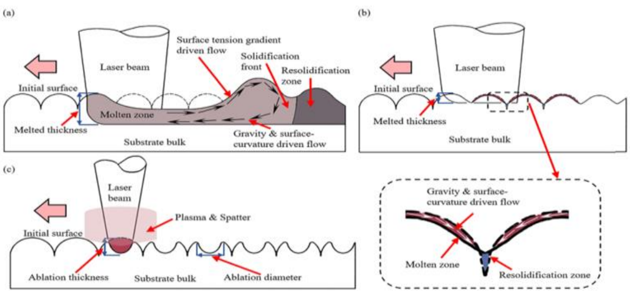

Fig. 2. Surface periodic waviness formation in (a) Surface over melting, (b) Shallow surface melting, (c) Laser surface ablation [4]

Investigations revealed that several barriers are impacting the widespread adoption of this technology. One of the many affirmed that it requires a very high upfront capital investment and operational costs. Secondly and perhaps most importantly, parameter optimization is non-trivial and requires significant research to optimize the large number of variables that are entirely process, material, and specific geometry. Empirical trials and numerical simulations are options, but they can be highly resource-intensive and costly to develop. In tandem, surface waviness can result from the governing melting mechanisms becoming unstable and oscillatory, which, paired with the fast-cooling rates, can lead to surfaces solidifying with periodic ripples. This can be a direct result of poorly optimized laser parameters leading to transient Marangoni forces. Self-excited capillary forces create capillary waves (ripples) along the phase boundary. These effects are highly driven by surface tension. When dealing with such sensitive microfluidic flows and localized precision. It can also be difficult to dampen external mechanical vibrations, which can create irregularities. Finally, the improvement and development of closed-loop feedback and sensor technologies for real-time enhanced control of processes are yet to come to full fruition. **Fig. 3** depicts the material cross-section hardening report due to laser polishing as published by Bordachev et al [5].

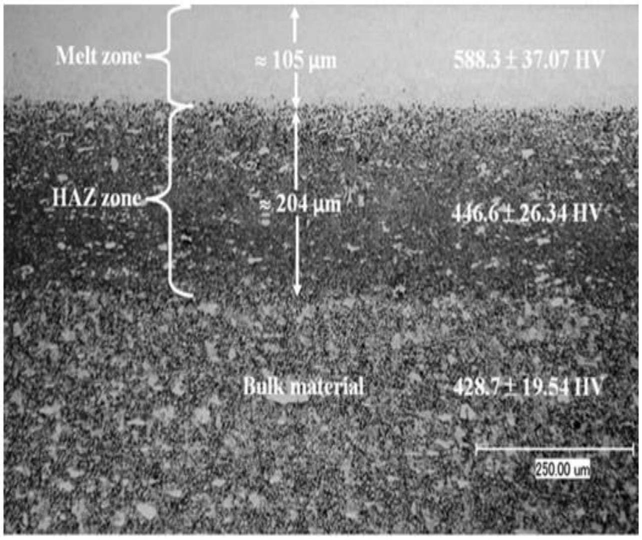

Fig. 3. Material cross-section hardening due to laser polishing [5]

1.2 Concept of Laser Resurfacing (Cleaning)

The laser resurfacing (cleaning) mechanism can be described by three submechanisms: surface irradiation, laser etching, and laser ablation [3]. While they are separate terms, the processes listed previously normally work in unison to create laser cleaning. The broader process of laser cleaning can be broken down into three main processes: dry laser cleaning, liquid-assisted laser cleaning, and laser shock wave cleaning [6]. Each of these methods uses similar yet different concepts to remove rust and dirt from surfaces. Unlike laser polishing, laser cleaning cannot fully rely on the melting and settling of the surface substrate to completely remove it. Rather, laser cleaning relies on the effects of pressure waves and expansion forces to impact the surface substrate, overcome any surface tension or van der Waals forces, and remove the substrate from the surface. Rust, dirt, and paint from surface substrates on structural steel components, as well as smaller parts that are assigned for refurbishment, are removed using the laser resurfacing method. The cleaning method adopted, the Liquid-Assisted Laser Cleaning Mechanism, and the corresponding Shock Wave Cleaning by Zhu et al. [6] in 2022 are presented in Figs. 4, 5, and 6.

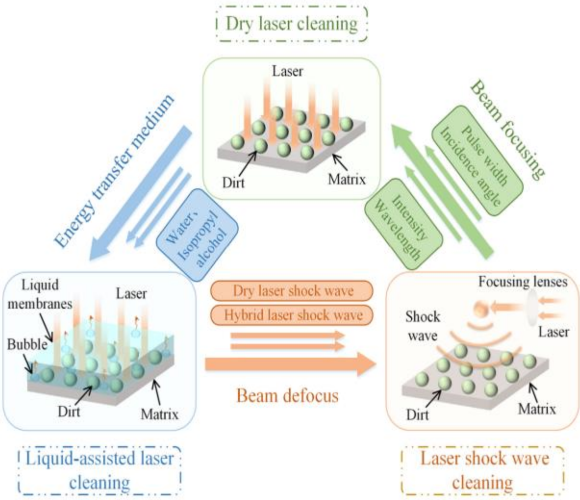

Fig. 4. Pulsed laser cleaning methods [6]

Dry laser cleaning is one of the most widely used methods. This method involves direct laser irradiation of the surface by focusing the laser beam on a specific area on the workpiece. The surface substrate and particles (usually paint or rust) absorb the laser beam's energy through a few mechanisms, and the unwanted particles are eventually dispersed from the surface once a high enough energy level is absorbed. These mechanisms include previously mentioned terms such as ablation and etching, where part of the substrate is vaporized as other parts are heated up enough to a point where the thermal expansion in the material causes them to detach from the surface they were bonded to [7] and [8]. Dry laser cleaning is free from liquid surface coating to help the cleaning process. Laser parameters such as power and pulse frequency determine how well a given surface is cleaned. Optimization and selection of these parameters will be discussed in further sections of this paper.

Literature also revealed that liquid-assisted laser cleaning, such as dry laser cleaning, can be performed with the additional step of adding a thin film of liquid to the surface. The necessity of adding this film of liquid is to reduce the possibility and effects of overheating of the base metal surface, which can occur in dry laser cleaning, resulting in unwanted damage to the workpiece, as well as a possible increase in the rate of particle removal. In this method, the liquid film is overheated. This results in the vaporization of the fluid film. Rapid evaporation and bubble expansion of this liquid have been shown to increase the magnitude of pressure waves produced by the laser, resulting in a more effective ejection of unwanted surface particles than in the dry laser cleaning case [9]. If the heating rate is sufficient, explosive phase change and evaporation can occur, enough to detach surface particles [10].

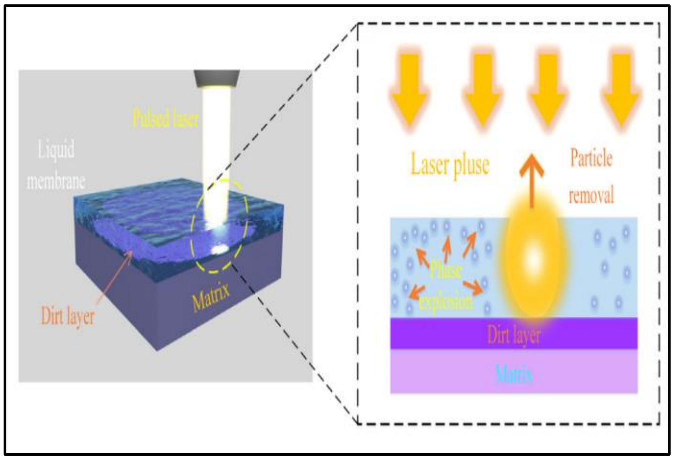

Fig. 5. Liquid-assisted laser cleaning mechanism [6]

Laser shock wave cleaning, as the name suggests, relies on miniature pressure (shock) waves that are formed by focusing the laser at a set distance above the work surface without direct laser impact on the surface. Through laser-induced breakdown of the ambient gas above the work surface, a strong enough shock is formed to remove small particles formed [11]. This method is not commonly used in rust removal, where particles are relatively large and bonded to the surface. However, it is useful in delicate situations where protection of the base workpiece is required.

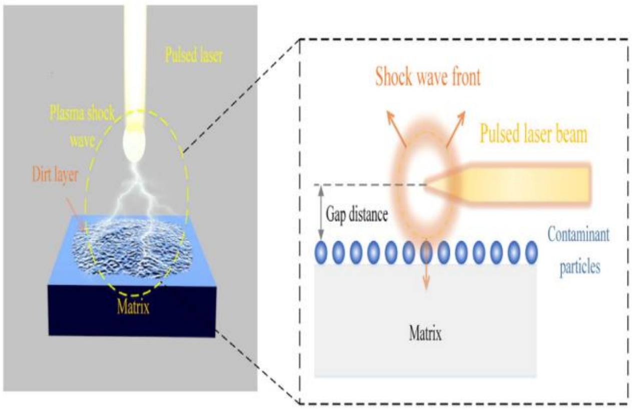

Fig. 6. Laser shock wave cleaning [6]

The preceding paragraphs laid some groundwork for how laser cleaning is applied to surfaces with larger contaminants, such as rust, as well as to smaller particles on delicate substrates. In the following sections of this paper, we will further explore how laser parameters are selected for the effective removal of surface materials. The focus will be on the dry laser cleaning method, as it is the most widely used and has proven effective for rust removal.

1.3 Concept of Cutting Techniques

The cutting process is one of the most advanced machining processes. It is often used with CNC software in sheet metal fabrication settings, where large quantities of sheet metal are cut before being fabricated. Using a laser beam focused on a small area on the workpiece, energy is absorbed by the work material. With this energy absorption, the material begins to heat up and eventually gets to a point where phase changes occur. The material melts and vaporizes, leaving behind a cut surface [12]. Laser cutting provides numerous advantages over other cutting methods, including minimal material removal, minimal distortion, and no tool wear [13].

There are a few parameters that should be observed in laser cutting, which determine how cut is left behind. Some of these parameters include surface roughness, kerf width, and heat-affected zone (HAZ) [14]. Surface roughness refers to the unevenness of the cut edge and cross-section and is undesirable in all applications. A better surface finish helps the fatigue life of the workpiece, and with a seamless editing or deburring of the cut material [15]. Kerf width is the width of the cut produced by the laser. The importance of this parameter can never be overemphasized in determining how well the geometric accuracy of the cut is. Lastly, the HAZ refers to the area around the cut where the material's microstructure changed, but the material did not melt [12]. The size of the HAZ determines how much of the material's physical properties changed after cutting [**Fig. 3**]. Changing physical properties can result in harder and more brittle material that is often unwanted, especially in processes where further machining is required. For example, plasma cutting is notorious for leaving a relatively large HAZ and a rough cut. This results in a harder material that can cause excessive wear on tooling used on the cut piece during machining [15]. Fig.7 shows the schematic explanation of the Kerf Width, HAZ, and Surface Roughness Illustration.

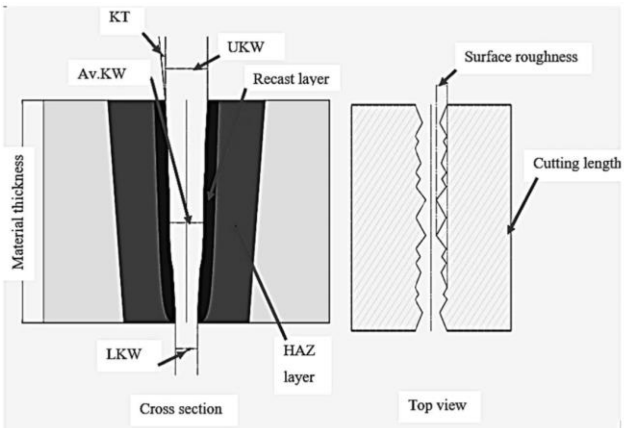

Fig. 7. Kerf width, HAZ, and surface roughness illustration [15]

2. Literature Review

Studies affirmed that laser surfacing, resurfacing (cleaning), and cutting enhance machining precision, efficiency, material performance, and surface integrity, optimizing manufacturing processes through reduced preparation time. Therefore, minimizing material waste and improving dimensional tolerances for engineering applications.

2.1 Laser Surface Finish Process

Laser surfacing represents a significant advancement in additive manufacturing, involving the sequential construction of material layers using a laser as the primary energy source. [8]. Dolgova et al. [16] analyzed deposition parameters for single laser tracks on austenitic steel 316L, identifying optimal conditions: 1,250 W laser power, 25 mm/s scanning speed, and ensuring precise geometric characteristics. Coatings containing iron, nickel, and tungsten carbide applied to 65 Mn steel samples enhance wear resistance. A schematic diagram of laser surfacing is shown in **Fig. 8**. Research affirmed that the abrasive resistance of a multicomponent charge with additives of 5 and 7 wt.% carbides are 2.45, 3.29, and 4 times higher than the base material of 65 Mn steel, Biryukov et al. [17] and Caggiano et al. [18]. When the propagation distance exceeded

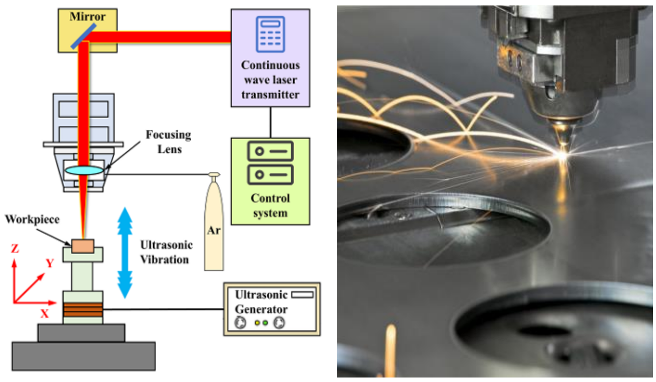

Fig. 8. Laser surface finishing schematic experimental setup [8] and sgproto.com)

10 mm, the defect signal in the acquired images displayed prominent noise points [19]. Laser polishing enhances surface quality, reduces roughness, improves density, and optimizes the mechanical properties of materials [20]. Abhishek et al. [21] and Caggiano et al. [18] applied innovative laser polishing with beam wobbling to Cr–Cu steel automotive parts. Results show that laser polishing enhances surface smoothness (62–78%) with limited microstructural changes using optimal wobbling parameters. Laser polishing significantly reduces surface roughness, enhances micro-hardness, and improves

specific properties of additively manufactured metals [22] and [23].

Additive manufacturing enables the creation of complex parts that traditional methods, such as machining or forging, cannot easily produce. Research highlighted that additive manufacturing parts require surface finishing to enhance quality and reduce the adverse effects of roughness [22] and [12]. Additive manufacturing (AM) is a dependable method for producing intricate and complex metallic components. Direct energy deposition (DED) is widely utilized in the production of metal alloys in additive manufacturing [4]. Vladimir proposed a laser surfacing technique that defocused and oscillated beams to charge particles suitable for testing 65 Mn coating steel for wear resistance. The results show that uniform coatings improve microhardness and enhance abrasive wear resistance significantly [18].

2.2 Laser Resurfacing (Cleaning) Process

Jing et al. [2] explored laser cleaning technology for isolator switches, analyzing principles and device design as a case study. Results show that optimal scanning speed and frequency improve cleaning efficiency and quality, providing effective rust removal without damaging the equipment base. Laser cleaning efficiently removes rust from steel surfaces while minimizing environmental impact. Optimal laser parameters prevent surface discoloration and do not affect material removal rate, showcasing its effectiveness and precision in industrial applications [24]. Narayanan et al. [25] and Gisario et al. [26] identified optimal laser parameters achieving material removal rates of 0.1–0.4 mm³/s with 90% accuracy. Maximum material removal occurred at 7.5–10 W, a hatch distance of 45–50 µm, a scanning speed of 875 mm/s, and a pulse repetition rate (PRR) of 50 kHz. The integration of response surface methodology with the second-generation non-dominated sorting genetic algorithm (NSGA-II) is a highly effective approach for optimizing laser cleaning parameters in rust removal applications [27]. Research demonstrates that optimal laser cleaning parameters include a laser power of 44.99 W, a cleaning speed of 174.01 mm/min, a scanning speed of 3852.03 mm/s, and a repetition frequency of 116 kHz. Zheng et al. [28] conducted a detailed investigation into the defocused nanosecond laser paint removal of mild steel substrates under atmospheric conditions, providing valuable insights for enhancing efficiency. Hence, reducing substrate damage in industrial applications. To safeguard steel bridges against corrosion, various advanced rust removal techniques were established. Vinod et al. [1] conducted a critical review of corrosion development and rust removal in steel bridges. The Schematic description of the laser cleaning process is presented in **Fig. 9**. The results revealed that Laser cleaning effectively removes rust, minimizes steel damage, and is environmentally safe, but it incurs a high cost. Laser cleaning is an innovative and emerging approach with significant potential for industrial applications [29]. Laser cleaning machines with a power of 100 W or above can effectively perform precision cleaning, widely promoted in the field of power systems [30]. The amplitude and the local standard deviation of the acoustic signal in the frequency range of 7–10 kHz gradually decrease to a steady value in laser paint cleaning [4], [7], and [18].

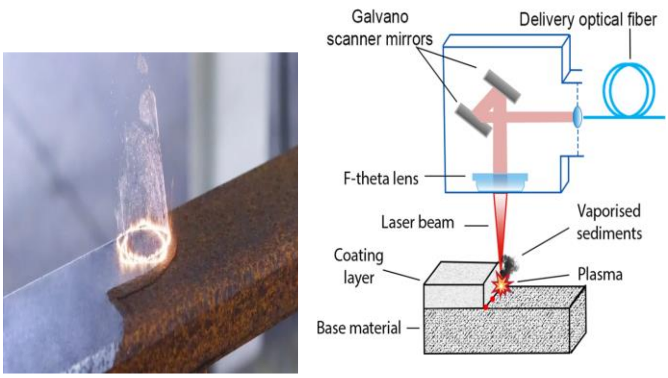

Fig. 9. Schematic description of the laser cleaning process [41], *sinbadlab.com.*

2.3 Industrial Cutting Techniques

Cutting technique is an industrial operation where a workpiece, such as metal, and the tool are moved over each other to shape the workpiece into the desired form through shaving, drilling, etc. The importance of cutting cannot be overemphasized. The techniques are highlighted among the advanced machining processes in modern manufacturing. They are frequently integrated with CNC software in sheet metal fabrication environments, facilitating the precise and efficient processing of large volumes of sheet metal before subsequent fabrication stages [5].

2.3.1 Laser Cutting Technique

Research affirmed that optimal laser cutting parameters achieve superior surface and kerf quality with reduced roughness and taper. Garcia-Fernandez et al. [31] investigated the impact of laser cutting parameters on the quality of cut surfaces and kerf. Using a comprehensive review of existing studies, analyzing performance through graphs, equations, and organized tables. Automation of tasks to replace manual processes, utilizing a control panel and ERP integration. Shortened production times, elimination of manual errors, and real-time updates on stock and production processes [32]. Ni et al. [33] examined the laser surface texturing (LST) of cutting tools to enhance the machining of titanium alloys such as Ti6Al4V. The result shows that LST enhances cutting-tool tribological performance, reducing wear, friction, cutting forces, and temperatures. Deng et al. [34] and Ni et al. [33] reviewed LPBF progress for Ti–6Al–4V in aerospace, biomedical fields. Adopt process parameters and thermal effects on forming properties. The report affirmed machining improvements in cutting force, tool wear, and surface quality. Optimized cutting parameters for acrylic using CNC laser cutting by applying the Taguchi method to test laser power, speed, and focus, giving smoother cuts and improved efficiency with precise parameters [35]. Laser cutting can never be overemphasized. Laser cutting is widely used for accurate, non-contact cutting of metals and non-metallic materials. **Fig.10.** depicts a schematic diagram of a laser cutting technique.

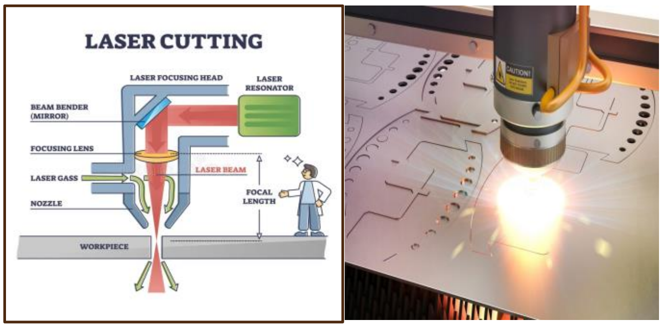

Fig. 10. Laser cutting techniques (Google.com and laserflow.com)

İrsel et al. [15] utilized a powered laser beam in laser beam cutting, plasma in plasma arc cutting, and a flammable gas-oxygen mixture in the oxygen cutting method to investigate the effects of various cutting methods and verify their advantages and disadvantages in cutting structural steels. It was discovered that plasma arc cutting increases hardness and reduces costs, while laser cutting provides superior precision and machinability. Naresh et al. [36] investigated the application of FEA, software nesting, and quality management to optimize the processing parameters: scanning speed, laser power, pulsing frequency, and gas pressure for laser cutting, minimizing equipment downtime caused by unnecessary stoppages.

2.3.2 Water Jet Cutting Technique

Krajca et al. [37] compared metal water jet cutting with laser and plasma cutting. The results show that water jet cutting proves to be the most versatile, eco-friendly, and effective for thick metal materials. The mechanical properties of the highly heat-sensitive acrylic can be considered by understanding the precise cutting process on a 40-watt CNC laser cutting machine. A water jet cutting technique utilizes thin water jets under high pressure with an abrasive slurry to cut the target material using erosion. It was patented in 1968 by a researcher in the USA, but developed rapidly in the 1980s. High-pressure water pumps are available in the range of 276 MPa to 689 MPa. This cutting method is common in the automobile industry, aerospace industry, construction engineering, chemical process engineering, environmental engineering, and industrial maintenance. Some of the leading companies are OMAX Corp. in Kent, Washington (largest), KMT Water System Inc., Kansas, WARD Jet Inc. in Ohio, Niche Inc., Massachusetts [37]. **Fig.11.** depicts a schematic diagram of a water-jet cutting technique.

Fig. 11. Water jet cutting technique (*Google.com and waterjet-cutting.com)*

2.3.3 Plasma Cutting Technique

A process that cuts through electrically conductive materials using an accelerated jet of hot plasma. This technology works by ionizing gas to create plasma, which can cut through materials. Plasma beam arcs can reach extremely high temperatures, typically around 25,000 °C, making them among the hottest sources used in industrial cutting applications. Steel and sometimes other metals of different thicknesses are cut using the plasma cutting technique. Leading companies include Riland Industry Group, Ltd in China, Panasonic in Japan, and TAYOR in China. **Fig.12.** depicts a schematic diagram of a Plasma Beam cutting technique.

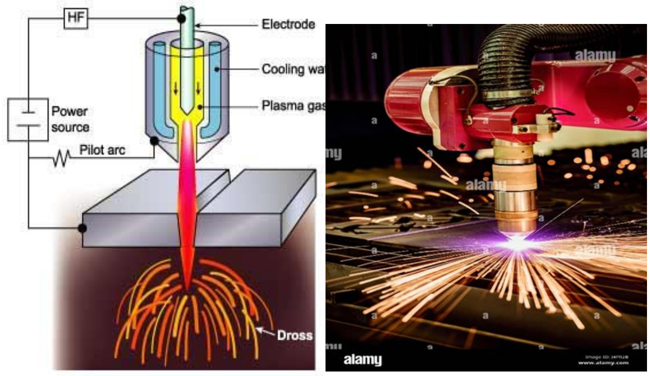

Fig. 12. Plasma beam cutting technique *(electricalfun.com and alamy.com)*

However, despite the progress made in existing research, studies in the field of laser, rust removal, surfacing, and cutting have primarily focused on the impact of a single factor, and few studies have considered the relationships between multiple factors and their overall impact on the quality of metal surface cleaning. This study aims to critique the viability of laser surfacing, rust removal, and cutting machine processes in industry. The following objectives are explored through a thorough literature review:

- Introduce the operations of laser surfacing, rust removal, and cutting
- Identify the advantages and disadvantages of these methods and compare them to other state-of-the-art techniques
- Identify the roles of different laser parameters on laser machining operations and determine how changing them affects the final product

The methodology adopted in this study is reported in Section 3; the main results obtained are discussed in Section 4; while the conclusions and recommendations are summarized in Section 5.

3. Methodology

3.1 Laser Surface Finishing Parameters

Though the physics behind laser remelting can be modelled numerically to a promising degree of accuracy, the parameters that control the laser's interaction with the material surface are critically important to the dynamics of the process and the quality of the result. Research conducted by Y. Cheng [8] reported that vital parameters for final material surfacing on the Ti6Al4V samples were laser power, laser scanning speed, and beam overlap, with the addition of ultrasonic vibration to prevent over-melting.

3.1.1 Laser Surface Finishing Experimental Setup

The experiment first establishes a numerical simulation of ultrasonic vibration-assisted laser polishing. A two-dimensional model in COMSOL Multiphysics was developed to simulate the melt pool. Assumptions of incompressible laminar flow, isotropic Ti6Al4V material properties, a Gaussian energy source confined to the surface, negligible frictional heating, and negligible material evaporation were made. The governing equations of transient heat transfer, latent heat via a specific heat formulation, and fluid mass and momentum conservation were applied along with volumetric forces for buoyancy, gravity, and ultrasonic vibration. This was modelled in a fine triangular mesh of 5 mm by 3 mm with cell sizes ranging from 0.001 to 0.035mm. The direct solver was then run to predict and model melt pool dynamics related to experimentally measured results (**Fig. 8,** *Laser surface finishing schematic experimental setup).*

The experimental laser system comprises an IPG YLR-500 laser, a laser polishing head, and a KUKA arm (model KR16-2). The laser system controls the laser to polish in the Y-direction. In contrast, the system applies ultrasonic vibration to the workpiece in the Z-direction, generating minute vertical oscillations. To systematically investigate the effect of ultrasonic vibration on the polishing, this study regulates the vibration amplitude by precisely controlling the ultrasonic power (UP). Specifically, when the UP was set to 5%, 10%, 15%, 20%, and 25%, the corresponding amplitudes were adjusted to 2.0 μ m, 2.7 μ m, 3.5 μ m, 4.2 μ m, and 5.0 μ m, respectively [38-39], [33], and [40]. The experimental specimens of Ti6Al4V were derived from the same batch to ensure uniform surface morphology. All specimens were uniformly brushed and cleaned with ethanol to remove any surface contaminants. The experimental Rz value and the simulation were found to be 1.745 μm and 1.586 μm, respectively. But a 9.1 % error. In UVLP, the experimental Rz value and the simulated Rz value were found to be 1.186 μm and 1.025 μm. Hence, an error of 13.6 %. These errors are within the acceptable range, confirming the accuracy of the simulation model [33].

3.1.2 Laser Power

Studies affirmed that low laser power, around 200 W, was insufficient to melt surface asperities due to suboptimal energy density. As the power increases to the range of 250–300 W, melting becomes more complete, and Marangoni and capillary flow dynamics begin to dominate, redistributing the material. Roughness fell to a minimum around 300W, but beyond this optimum, over-melting begins to occur, inducing oscillatory flows and creating waviness. The effects of laser cutting parameters on oxygen content, material removal rate, as proposed by D'aurelio et al. [38], are illustrated in **Fig. 13.**

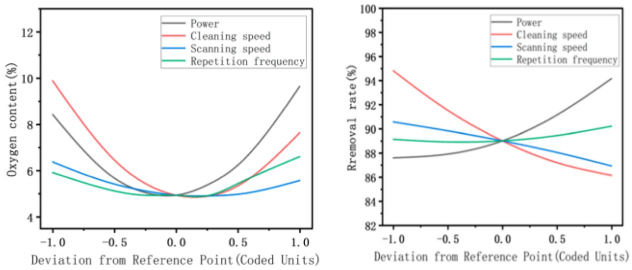

Fig. 13. Impact of interaction on various factors on oxygen & removal rate contents [38]

3.1.3 Laser Scanning Speed

Scanning speed at lower laser powers has virtually no impact, as it shortens interaction times between the material surface and the localized energy deposition from the laser. With a sufficient power level (> 250 W), experimental results indicate a positive correlation between scanning speed and surface roughness. As scanning speed increases, roughness is reduced by limiting excessive heat deposition, which promotes a thinner, better-controlled melt pool. Optimal conditions for reducing scanning speed surface roughness were determined experimentally at various laser power intensities (**Fig. 14).** These conditions were established at a laser power of 300 W and a scanning speed of 25 mm/s [33].

3.1.4 Laser Beam Overlap

Beam overlap dictates how successfully the laser surface is uniformly treated by the material surface. Moderate overlaps (25%-75% of beam diameter) produced consistent remelting of previously treated and solidified tracks. This was observed to have an inverse relationship with surface roughness, where roughness is reduced as the overlap increases. However, too high an overlap (> 75 %) leads to excessive heat accumulation, extending the duration of the surface being in a molten state, fostering thermal stresses, and coarser resolidified grain structures. This, in turn, reduces material surface hardness. Across all overlap rates tested, the combination of 300 W power, 25 mm/s scan speed, and a moderate overlap yielded the lowest roughness.

3.2 Laser Resurfacing (Cleaning) Parameters

Like all laser machining processes, the quality of a laser-cleaned surface depends heavily on the input parameters set for laser cleaning. For dry laser cleaning, the main forces that must be overcome to remove particles from the surface are van der Waals and electrostatic forces [6], [41 - 42]. For particles smaller than a few microns, van der Waals forces are dominant and can be represented by the equation:

$$F_v = \frac{hr}{8\pi z^2} + \frac{hr_c^2}{8\pi z^3} \tag{1}$$

Where r, h, and z are the radius of particles, the Van Der Waals constant, and the atomic spacing between the particles and the surface. The subsequent goal is to create a cleaning force greater than the Van Der Waals force, which will result in the ejection of particles. For larger contaminant particles, more energy is required to overcome the combination of electrostatic and van der Waals forces. The most important parameters for cleaning efficiency were identified as laser power, wavelength, pulse width, and scanning speed. They described an empirical formula for cleaning efficiency as:

$$C_E = cX \times \left(\frac{P}{A}\right)^n \times \left(\frac{t''t}{\tau_p t'}\right)^{n+1} \times \frac{1\,(\mathrm{m}^2)}{A\,(\mathrm{m}^2)} \tag{2}$$

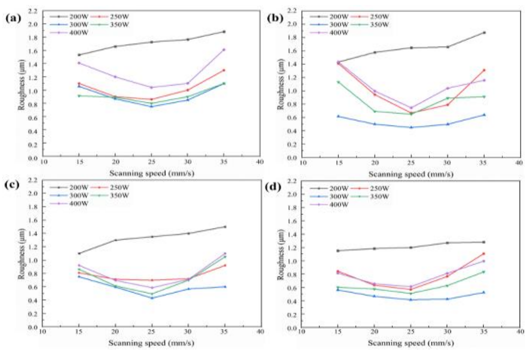

Fig. 14. Laser power and scanning speed effect on surface roughness at various beam overlap rates/amplitude of (a) 2.0%, (b) 50%, (c) 75%, (d) 85 % [33]

Where c and n represent the empirical constants depending on the target conditions and laser parameters, X represents the thickness of the contaminant, P is the average power, A is the area irradiated by the laser beam on the target surface, τ_p is the pulse width, and t is the pulse duration. The result also shows that laser wavelength affects the absorption and reflectivity coefficients of the surface and affects the rise in temperature of particles lying on this surface. This is relevant in the following equation for the cleaning force of the laser:

$$F = \gamma E \Delta T(d, t) \quad (3)$$

Where: γ, E, ΔT, and (d, t) are the linear thermal expansion coefficient, elastic modulus, and temperature rise at the surface housing the particle, respectively [6].

3.3 Cutting Techniques Parameters

The industrial cutting methodology adopted in this study involves a comparative analysis of three metal-cutting techniques (water jet cutting, laser cutting, and plasma cutting). Hence, each is described in terms of its operational principles, advantages, and limitations. This structured approach ensures a comprehensive comparison of the cutting techniques, providing valuable insights for selecting the most suitable method for specific applications.

3.3.1 Concept of Data Collection

In this research, data are gathered from existing literature and experimental observations to evaluate the performance of each cutting method [15]. The techniques are compared based on these six key parameters:

- Versatility of technique cuts (economy cuts).
- Environmental impact
- Material thickness limitations
- Thermal deformation
- Cut surface quality
- Ease of programming

3.3.2 Cutting Experimental Setup

Works of literature affirmed that for water jet cutting, high-pressure water mixed with abrasive particles is used to cut materials. However, laser cutting employs a focused laser beam and technical gas to achieve precision cuts. Plasma cutting utilizes a high-temperature plasma arc to melt and remove material [19], [37], and [43 - 40]. In the comparative analysis of these three metal-cutting techniques, the effects of each method on the workpiece, including thermal deformation, surface quality, and material hardening, were also examined. The summary of the performance of the three methods across the evaluation criteria was presented in a tabular form in the section of this study. Hence, the strengths and weaknesses of each technique were also featured in the results.

4. Results and Discussion

4.1 Laser Surface Finishing Parameter Optimization

When conducting laser surface finishing on a material, it is important to understand the material properties of the parts being worked on to develop an optimal solution for laser treatment. Laser parameters, such as laser power, scanning speed, and beam overlap, are most prevalent. The final geometry of the part has an impact on the process. Hence, the criticality of having a properly programmed robotic or CNC control apparatus to ensure that the entire material surface can be treated.

4.2 Laser Resurfacing (Cleaning) Parameter Optimization

Similarly, for laser cleaning, the parameters of laser power, scanning speed, and pulse width impact the quality of the process and final surface finish. Optimizing the laser power and scanning speed to fully ablate corrosion, thereby keeping the underlying material surface intact. Due to the nature of laser ablation, laser pulses are used for high-energy deposition over short periods. As stated above, it is critical to find a pulse width that is narrow enough to deposit a high energy density to ablate the corrosion, but wide enough not to leave craters in the cleaned material surface. Due to the substantial costs often associated with trial-and-error approaches in these manufacturing techniques, it is highly beneficial to develop comprehensive numerical models that simulate the dynamics of laser-surface interactions and can be validated against experimental results, streamlining the parameter optimization process. The theoretical and empirical formulas above can also be used to estimate proper laser parameters.

Equation 1 suggests that increasing the laser intensity, either by increasing laser power or decreasing the focus area of the laser, will increase the cleaning efficiency. Similarly, Equation 2 suggests that the lower the wavelength of the laser, the greater the cleaning efficiency due to greater energy absorption by the surface and particles. The pulse width is a quite important parameter for determining how well the surface is cleaned in pulse laser cleaning. Zhu et al. [6] show, as expected, that an increase in pulse width results in greater energy absorption by the surface and particles. An increase in this energy absorption results in larger particles being able to be removed, but also increases the likelihood of damaging the surface. Narayanan et al. affirmed that slower scanning speeds result in deeper craters in the surface material [29]. This increases the amount of material to be removed at the cost of more damage to the surface. Much like pulse width, a slower scan speed allows the surface and particles to absorb more energy. It was observed that for a given laser power, there exists a laser scanning speed range that results in a change to the crater depth created by the laser, suggesting an optimal scanning speed range for different laser powers and materials.

4.3 Cutting Techniques Parameter Optimization

Conclusions on these cutting techniques are drawn from experimental results in various kinds of literature. A comprehensive comparative analysis of waterjet, plasma, and laser industrial cutting techniques, incorporating key parameters such as versatility, environmental impact, material thickness limitations, thermal deformation, cut surface quality, ease of programming, cutting speed, workpiece geometry, operational costs, cutting precision and other critical factors is thoroughly presented in **Table 1**, based on the framework proposed by Krajcar et al. [37].

4.3.1 Key Parameter Result

Table 1: A comparative analysis report of water jet, laser, and plasma cutting techniques

Method of cutting	Abrasive Water Jet	Plasma beam	Laser beam
Speed	Slow	Fast	fast
Operating costs	Topmost	Lower	Lower
Precision cutting	High	Impossible	Higher
Size details	Small and large	Large	Small and large
Shapes	Complicated	Simple	Complicated
Thermal deformation	Lack	Yes, wider area	Yes, a small area
Material suitable for intersection	Most of the solid	Metals and conductive materials	Homogeneous with no reflective bodies
Materials covered with rust	Very good	Average	Good
Composite	Yes	No	No
Material hardening	No	Yes	Yes
Hazardous vapors	No	Yes	Yes
Multilayer cutting	Possible	Impossible	Impossible
Burr formation	Minimal	Yes	Yes
Material thickness	Thick and thin	Medium and thick	Thin and medium

The methodology section of this study emphasizes six critical cutting parameters identified through a comprehensive review of existing literature and experimental observations. These parameters were employed to assess the performance of waterjet, laser, and plasma cutting techniques. A concise summary of each parameter, as derived from the detailed literature review, is presented below.

- **Versatility:** Research affirmed that waterjet cutting excels in versatility, handling various materials, including reflective and non-conductive ones, unlike laser and plasma methods.
- **Environmental Impact:** Highlighted water-jet cutting is the most eco-friendly, using recyclable abrasives and water, while laser and plasma emit hazardous fumes.
- **Material Thickness Limitations:** Waterjet cutting handles thick materials over 100 mm, plasma cuts up to 160 mm, while laser struggles beyond 30 mm thickness.
- **Thermal Deformation:** Waterjet cutting avoids thermal deformation, preserving material integrity, whereas laser and plasma cause heat-induced structural changes.
- **Cut Surface Quality:** Waterjet cutting produces smooth, burr-free edges, plasma is rough and inaccurate, and laser cutting offers precision but heat-affected zones.
- **Ease of Programming:** All three methods allow easy programming, but water jetting requires minimal setup, ensuring stable material placement.

5. Conclusion

In conclusion, laser surfacing, resurfacing, and cutting are valuable laser machining operations that provide advantages not previously known to the machining industry. These state-of-the-art techniques aid in the sheet metal fabrication industry, additive manufacturing, and steel rehabilitation and cleaning, among others. While still considered the leading edge of technology, research trends show these methods are destined to become a staple in the machining industry for decades to come. The main results obtained from this study are:

- Laser surfacing improves surface finish on simple and complex geometries for a variety of materials through remelting and solidification of the work surface. Similarly, thermal expansion as well as pressure waves can remove unwanted particles such as rust and dirt in the case of laser cleaning (resurfacing). Laser cutting uses a High-Powered laser to create a melt pool that eventually cuts through material in a precise manner.
- These methods can efficiently and precisely perform across a wide range of complex geometries with little waste and no tool wear. Though difficult parameter selection and relatively high cost impose a barrier to using such technologies.

- The laser parameters of laser power and scanning speed are the most important parameters for determining the success of a laser machining operation; hence, they must be carefully selected based on the material and condition of the workpiece.

Authors recommend more findings in the areas of laser parameter selection and optimization, process implementation, and integration into existing manufacturing processes. While these methods show promise, many of the results seen in current research are on small scales in controlled environments. An utmost priority is required to achieve a better understanding of how to accurately set laser parameters, to process specific materials and workpieces without a trial-and-error method. The development of numerical methods and simulations has been explored, but general use cases have yet to be developed. In the additive manufacturing area, there is an opportunity to implement a laser polishing workflow, which would make the process much more desirable and cost-effective. Lastly, laser cleaning requires relatively large machines that might prohibit this method from being used in some cases. Hence, continuous studies to develop more mobile handheld technologies should be encouraged.

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