Non-Traditional Machining Techniques in Manufacturing Industries – An Overview

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Abstract. This comprehensive study provides an in-depth analysis of non-traditional machining techniques in the manufacturing industry. Focusing on mechanical, electrochemical, chemical, and thermal machining processes, the research explores recent advancements and their implications. The study adopts the action research method to gain a deeper understanding of the challenges associated with these techniques. Through a thorough examination of the machining processes, this work delves into various concepts, including the operations involved in each process and their corresponding outcomes. The analysis sheds light on the significance of non-traditional machining in the manufacturing industry, highlighting its potential for producing complex components and meeting design requirements that traditional machining methods may struggle to achieve. By exploring recent developments in non-traditional machining, this study aims to provide an overview of the advancements made in this field. It emphasizes the importance of understanding these techniques to unlock their full potential and enhance manufacturing capabilities. The findings of this research contribute to the existing knowledge base and serve as a valuable resource for professionals and researchers in the field of non-traditional machining.

1 Introduction

In ancient times, during the early stages of human civilization, tools were crafted primarily using stones. However, as time progressed, mankind made significant advancements in materials technology, leading to the discovery and utilization of other substances, such as iron [1], [2]. Fast forward to the present day, material products manufactured in the 20th century have evolved to become highly durable and sophisticated. As a result, a majority of these materials have become non-machinable, posing a challenge to the manufacturing industries. To address this challenge, the industry turned towards the development and implementation of advanced materials such as alloy steel, carbide, ceramics, and diamond as cutting tools [3]. These materials possess unique properties that make them suitable for working with non-machinable substances. Alloy steel, for instance, is a combination of different metals, resulting in enhanced strength and resistance to wear. Carbide, composed of carbon and a metal such as tungsten, offers exceptional hardness and durability. Ceramics and diamond, known for their extreme hardness, provide excellent performance when used as cutting tools.

The inability to machine these modern materials presents a hurdle for manufacturing industries [4]. Traditional machining techniques, such as cutting, drilling, and grinding, may not be effective or feasible for these advanced materials. As a result, innovative manufacturing processes, such as electrical discharge machining (EDM), laser cutting, and abrasive waterjet cutting, have been developed to overcome this challenge [5]. These techniques utilize the unique properties of these materials and employ controlled energy sources to shape, cut, or form them precisely.

Overall, the fundamental difference between conventional and non-traditional machining lies in the approach to material removal. While traditional machining relies on the application of sharp tools for plastic deformation, non-traditional machining encompasses a range of energy-based methods that allow for the machining of advanced materials, complex geometries, and achieving superior surface finishes and accuracies [6]. Figure 1 illustrates some of the tools that were

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used in ancient times. In contrast to these old-style machining methods, such as milling, turning, and drilling, which are considered conventional or traditional machining processes, there exist more advanced methods known as non-traditional machining (NTM).

Fig. 1. Early age used tools

1.1 Classification of Non-traditional machining

Unlike conventional machining, which has remained largely unchanged since the earliest days when humans fashioned wheels out of stone, non-traditional machining involves the use of technologically advanced processes that do not rely on sharp tools for material removal. Non-traditional machining encompasses a newer group of machining processes that utilize various forms of energy to remove material, without the need for sharp cutting edges [1], [7]. These energy-based processes can involve mechanical, electrical, thermal, and chemical energies, either individually or in combination, to achieve material removal or eliminate excess material. The advantage of non-traditional machining lies in its ability to machine materials using energy processes rather than sharp cutting tools. This approach opens up possibilities for machining tasks that are difficult or impractical to accomplish through conventional means. By harnessing mechanical, electrical, thermal, or chemical energies, non-traditional machining processes provide alternative methods for material removal and shaping. The classification of non-traditional machining is illustrated in Figure 2. By eliminating the reliance on sharp cutting tools, non-traditional machining expands the range of possibilities in manufacturing and allows for greater flexibility in machining different materials and achieving complex shapes. These advanced processes offer new avenues for precision machining, particularly in applications where conventional methods may be limited [3].

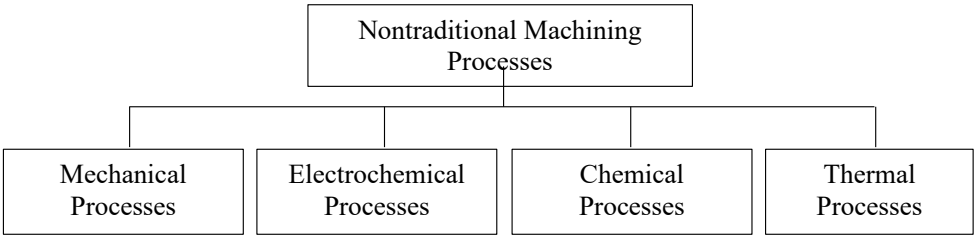

Fig. 2. Classification of non-traditional machining processes

1.2 Research Approach

This paper adopts a deductive and qualitative research approach to investigate non-traditional machining techniques. It aims to provide a comprehensive understanding of these techniques and their significance in the manufacturing industry by covering a wide range of concepts, including the operational aspects and corresponding outcomes. Emphasizing the importance of keeping up with technological developments, the research highlights the need to effectively meet design requirements and enhance productivity. Drawing on years of experience in the field, this study aims to provide valuable insights into non-traditional machining techniques and their practical implications. The paper is structured as follows: Section 2 provides a concise overview of mechanical energy-efficient processes, exploring their applications and advantages. In Section 3, the focus shifts to electrochemical machining (ECM) processes, examining their principles and advancements. Section 4 delves into chemical machining (CHM) processes, discussing their uses and potential environmental considerations. Furthermore, Section 5 investigates thermal machining processes, analyzing their characteristics and suitability for different applications. To foster future development in the field, Section 6 presents the

research outlook, highlighting potential avenues for further investigation and advancements. Finally, the paper concludes with Section 7, offering a comprehensive summary of the research findings. It emphasizes the key takeaways and contributions of the study, underscoring the practical implications and potential benefits of incorporating non-traditional machining techniques in the manufacturing industry.

2 Mechanical Processes (Energy Efficient)

In the vast field of engineering, the manufacturing and processing of products play a crucial role both technologically and commercially. Throughout the manufacturing process, various techniques are employed to process materials, including machining for precise dimensioning and tolerances, as well as cutting processes [8]. Cutting processes are widely utilized for shaping materials and removing excess material, and there are numerous methods available for cutting. This section specifically focuses on cutting processes achieved through the utilization of mechanical energy. Mechanical energy processes involve the erosion of material using a fluid and/or abrasive that moves at high velocities. There are several methods through which mechanical energy processes can be implemented. These processes are explained below:

2.1 Ultrasonic Machining

Ultrasonic Machining is classified as a non-traditional machining process that involves the use of a tool oscillating at low amplitudes, typically ranging from 25 to 100 microns, and high frequencies, typically ranging from 15 to 30 kHz [9]. In this process, a slurry containing abrasives is utilized, where the abrasive particles are rubbed against the workpiece by the vibrating tool. The underlying principle of ultrasonic machining is predominantly mechanical. It is primarily employed for processing hard and brittle materials, including both electrically conductive and non-conductive ones [9]. When the material's hardness exceeds 40 HRC, ultrasonic machining is the preferred choice [9,10].

During the ultrasonic machining process, a slurry consisting of abrasives is propelled at high velocities against the workpiece using a tool vibrating at high frequencies and small amplitudes. The tool oscillations occur perpendicular to the workpiece, and the tool is gradually fed into the workpiece to allow the abrasive particles in the slurry to remove material (shown in figure 3). This material removal shapes the profile of the tool into the workpiece, enabling the creation of non-circular holes or holes following curved axes rather than straight lines. This machining technique is applicable to brittle and hard materials such as carbides, ceramics, and glass. Moreover, it can also be utilized for certain metals, including titanium and stainless steel [9–11].

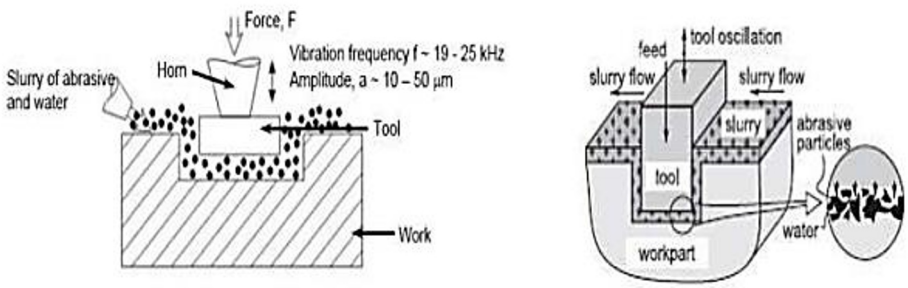

Fig. 3. Schematic of Ultrasonic Machining

The four main components of ultrasonic machining are the high-power sine wave generator, transducer, tool, and tool holder [12]. The generator increases electrical power frequency, the transducer converts electrical energy into mechanical vibrations, and ductile materials are commonly used for the tool to reduce wear rate. The tool holder connects the tool to the transducer, allowing energy transfer and amplification of vibration amplitude. It is important to carefully select process parameters to achieve desired machining outcomes, considering factors such as tool properties and abrasive characteristics. Ultrasonic machining offers a solution for effectively machining challenging materials like glasses, ceramics, and tungsten carbide, and it enables the machining of extremely hard materials such as titanium and its alloys [11].

2.2 Water Jet Cutting

The process known as high-pressure water jet machining involves the utilization of water propelled at high velocity and pressure, which is directed towards the surface of the substrate [13]. This technique is often automated using CNC or robots to ensure safe operation, as the high-pressure water can pose risks. By controlling the movement of the nozzle

along a predetermined path, precise cutting can be achieved. High-pressure water jet machining is particularly effective for cutting thin slits with minimal material loss. It finds application in various materials, including plastics, composites, textiles, floor tiling, leather, carpets, and cardboard of different sizes [13,14]. However, it is important to note that this method is not suitable for fragile or brittle materials like glass, as they may be prone to damage during the cutting process.

2.3 Abrasive Water Jet Machining

Abrasive Water Jet Machining is a highly effective process specifically developed for working with metals. While the fundamental principle of this machining method is similar to water jet cutting, the addition of abrasives to the jet stream enhances its cutting capabilities, enabling precise and efficient metal machining. The abrasives play a crucial role in the process, as they assist in eroding the metal surface and facilitating the material removal process. When working with metals, selecting the appropriate type of abrasive, as well as determining the grit size and characteristics, becomes essential [15,16]. The choice of abrasive depends on the specific machining operation and the material being machined. Various types of abrasives, such as garnet, aluminum oxide, or silicon carbide, can be utilized. The grit size refers to the particle size of the abrasive material, and it can range from coarse to fine, depending on the desired cutting outcome and the metal's properties. Additionally, the grit characteristics, including shape and hardness, are carefully considered to ensure optimal cutting performance and surface finish.
The incorporation of abrasives into the water jet stream transforms the high-pressure water into a powerful cutting tool capable of efficiently machining metals. As the water jet exits the nozzle, it propels the abrasive particles towards the metal surface with tremendous force. The combination of the high-velocity water and the abrasive particles effectively erodes the metal, gradually removing material and creating the desired shapes and features [16]. One of the advantages of abrasive water jet machining is its versatility. It can be employed for various metalworking applications, including cutting, shaping, and profiling [17]. Whether its precision cutting of intricate patterns or rough machining of thick metal sheets, abrasive water jet machining offers flexibility and accuracy. The process is also known for its ability to produce smooth and burr-free edges, reducing the need for additional finishing operations [16,17]. To provide a visual representation of the abrasive waterjet machining process, Figure 4 illustrates the key components and the interaction between the abrasive-laden water jet and the metal workpiece. This illustration showcases the dynamic nature of the process, highlighting the intense erosion caused by the combined forces of the high-pressure water and the abrasives.

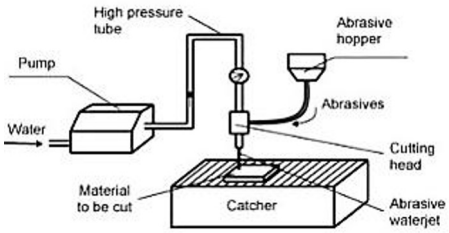

Fig. 4. Illustration of abrasive water jet machining

2.4 Abrasive jet Machining

Abrasive Jet Machining is a process that utilizes a high-velocity gas, along with added abrasive particles, for various finishing operations [15], [16]. Unlike water jet or abrasive water jet machining, this method employs gas as the fluid medium to propel the abrasive particles onto the work material. It is typically performed as a manual operation, where an operator controls the nozzle for tasks such as trimming, cleansing, and final polishing of the workpiece. This technique is commonly applied to sheet materials (such as glass, ceramics, or certain metals) that are hard, fragile, or brittle, resembling the concept of sandblasting [18]. In abrasive jet machining, the high-velocity gas, often compressed air, acts as the driving force for propelling the abrasive particles towards the work material. The abrasive particles are mixed with the gas stream, creating a focused jet that impacts the surface of the workpiece. The operator carefully directs the abrasive jet to achieve the desired finishing effects. This process finds particular application in situations where delicate or brittle materials need to be worked on [18],19]. By using a gas medium, the operator can exert precise control over the abrasive jet, allowing for intricate trimming or shaping operations. Additionally, abrasive jet machining is effective for cleansing surfaces by removing contaminants, coatings, or unwanted layers from the workpiece. It can also serve as a final polishing step to enhance the appearance and smoothness of the material [18].

2.5 Abrasive Flow Machining (AFM)

Abrasive Flow Machining (AFM) is a specialized machining process that involves the extrusion of a viscoelastic polymer mixed with abrasive particles to remove material and achieve desired surface finishing effects [20]. In AFM, two vertically opposed cylinders are utilized to create a reciprocating flow of the abrasive medium between the tooling and the workpiece. Several process parameters significantly impact the performance of AFM, including the number of cycles, extrusion pressure, grit concentration, grit size, and fixture design [20-22]. AFM finds wide-ranging applications in industries such as aerospace, semiconductor, and automotive. Its unique characteristics and behavior make it an attractive solution for reducing costs by replacing high-cost manual finishing operations in overall manufacturing systems [20].

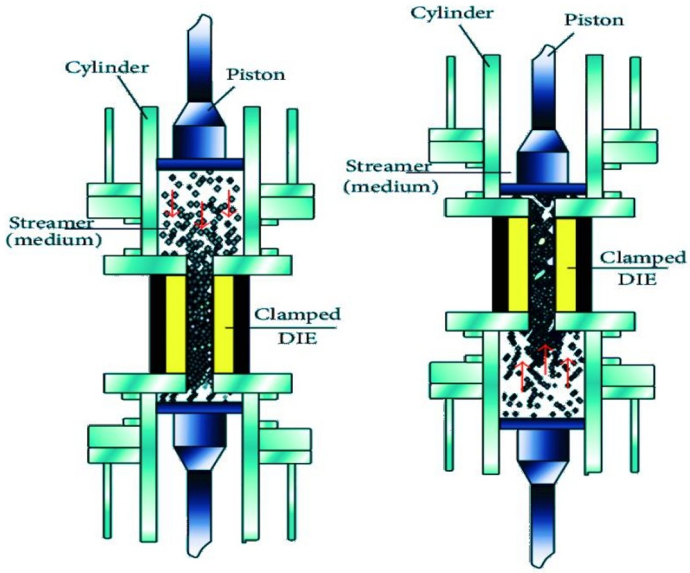

Fig. 5. Abrasive flow machine [23]

3 Electrochemical machining (ECM) processes

Electrochemical machining (ECM) is a non-contact process that utilizes an anodic solution to remove material, regardless of its hardness. Unlike conventional mechanical processes, ECM does not introduce machining stress, tool wear, or recast layers, making it suitable for a wide range of applications in industries such as aerospace, automotive, and medical. The ECM process involves the formation of an electrode system composed of the workpiece and the tool [24]. The workpiece is connected to the positive pole of an electric power source, and material removal occurs through electrochemical reactions upon the application of voltage to the electrodes. The accuracy of ECM primarily depends on the shape of the tool electrode and the gap thickness between the tool electrode and the workpiece [25,26]. However, in standard continuous current ECM, it becomes challenging to execute the process with gaps less than 0.2 mm due to various factors. These factors include electrolyte heating caused by electric current flow, gas emission at the electrode, slow speed of electrolyte flow, formation of solids in the electrolyte, and high variation of conditions in the curvilinear geometries of the inter-electrolyte gap. Despite these challenges, ECM offers numerous advantages over conventional machining, such as high material removal rates without tool wear, improved surface finish, and enhanced machinability regardless of material hardness. Consequently, extensive research and reviews of ECM remain pivotal in further advancing the understanding and optimization of the process [25–27].

3.1 Electrochemical Machining (ECM)

Electrochemical Machining is a complex machining technique that involves the removal of material from a workpiece through an electrochemical process [24]. It can be considered as the reverse of electroplating, as material is removed instead of being added to the surface. This process shares similarities with electrical discharge machining, as it involves the passage of high current through the electrodes of the machine and the workpiece. The workpiece, serving as the anode

(positive pole), gradually depletes and transfers material through the flowing electrolyte to the tool, which acts as the cathode (negative pole) [24,[25].. To prevent plating from occurring on the tool or electrode, the electrolyte rapidly flows between the poles, removing the depleted material. Common materials for the tool or electrode include copper, stainless steel, or brass. The design and size of the tool must consider the necessary opening between the poles to facilitate the flow of electrolyte.

$$\mathbf{V = CIt} \quad \ldots \qquad (1)$$

According to Faraday's law (Equation 1), the volume of metal removed (V) is proportional to the specific removal rate (C), current (I), and time (t). The amount of material dissolved depends on the quantity of electricity passed through the system. Electrochemical machining finds application in various scenarios, including die-sinking with irregular shapes, such as for plastic molding, simultaneous drilling of multiple holes, machining irregularly shaped holes (non-circular), and deburring processes.

Electrochemical Machining (ECM) offers a wide range of applications, although it is primarily suitable for machining parts with unique geometries due to the tooling costs involved. Figure 6 provides examples of components that have been successfully machined using ECM. In this section we will explore the various areas of application for ECM. In the aerospace industry, ECM finds extensive use in machining critical components. Turbine blades, which require intricate shapes and precise contours, can be efficiently machined using ECM. The process ensures the desired aerodynamic profiles of the blades are achieved with high accuracy. Additionally, ECM is employed for manufacturing airframe components such as fuselage sections and wings. These complex components with irregular shapes and critical tolerances can be effectively machined using ECM. Engine blade airfoils, vital for optimal engine performance, are another area where ECM excels. ECM allows for precise shaping and profiling of these airfoils, ensuring efficient airflow. Moreover, ECM is applied in machining aircraft panels, which play a significant role in structural integrity and aerodynamics.

Fig. 6. Applications of ECM

Apart from aerospace applications, ECM is widely utilized for deburring of components. The non-contact nature of ECM and its ability to access complex geometries make it suitable for removing burrs, resulting in improved part functionality and aesthetics. Furthermore, ECM is employed for drilling multiple holes simultaneously, making it an efficient process for achieving hole patterns with high accuracy. Die sinking, which involves machining cavities with irregular shapes, is another application where ECM demonstrates its value. ECM's ability to precisely shape and contour components allows for the creation of intricate features. Additionally, ECM is employed in machining micro-components, where its high precision and non-contact nature make it ideal for achieving miniature parts with complex geometries. ECM offers several advantages over conventional machining processes. It enables high surface finish (up to 25 µm) and accuracy, making it suitable for applications requiring fine details. The absence of mechanical and thermal stresses during ECM ensures that delicate and fragile components can be machined without the risk of damage. ECM also exhibits minimal tool wear, reducing the need for frequent tool replacements. The process is capable of machining parts with difficult-to-reach areas, thanks to its non-contact nature. Deep holes can be accurately achieved using ECM, making it valuable in various industries.

ECM is effective in removing burrs from parts, further improving the quality of machined components. However, ECM has some limitations to consider. The workpiece to be machined must be electrically conductive, as ECM relies on ion exchange for material removal. Sharp edges cannot be effectively machined using ECM due to the erosion of electrolytes from the edges. ECM processes require high power consumption, and the equipment involved can be costly to acquire and maintain. Despite these limitations, ECM remains a valuable machining technique for specialized applications. The operation of an ECM involves positioning the cutting tool, typically a grinding wheel, as the cathode and the metal piece as the anode. An electrolytic fluid is pumped between the workpiece and the grinding wheel, facilitating electrochemical reactions at the workpiece surface. Material removal occurs through oxidation, and oxide film deposits are subsequently removed by the grinding wheel. This process ensures smooth edges and curves with desired tolerances, while generating minimal heat to avoid workpiece distortion. The removed material is collected within the electrolytic fluid. Sodium

chloride and sodium nitrate are commonly used as electrolytes in ECM. Figure 7, a and b compares the conventional electrochemical process with the principle applied in electrochemical grinding operation, respectively.

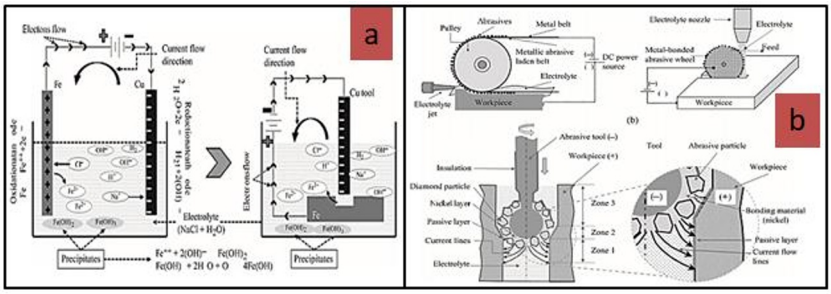

Fig. 7. (a) Electrolytic process (b) Electrochemical Grinding process [13]

3.2 Electrochemical Deburring

Electrochemical deburring as depicted in Figure 8 is a precise finishing process used in high-precision manufacturing and machining [28]. Unlike traditional drilling methods, electro-chemical deburring (ECD) focuses on localized burr removal [29]. The deburring process involves positioning the workpiece on a non-metallic locator, which precisely aligns an electrode with the burr(s) on the surface. By applying a positive charge to the workpiece (anode) and a negative charge to the electrode (cathode), along with the presence of an electrolyte solution, the deburring process is initiated. To ensure effective deburring without compromising the component, tooling, or equipment, the electrolyte solution is directed under pressure to the gap between the burr and the electrode. Before the application of current, the electrolyte stream flushes out any loose chips that may hinder the process. As the burr undergoes anodic metal dissolution, a controlled radius is formed, resulting in consistent deburring from part to part and lot to lot [28-30].
Proper fixturing is crucial in ECD. A standard fixture consists of a plastic locator that securely holds the part and isolates or "masks" areas that do not require deburring, along with a highly conductive metallic electrode. The electrode's contour is designed to match the specific dimensional characteristics of the targeted deburring area. The locator or electrode regulates the flow of electrolyte during the process, depending on the fixture's design determined by the engineering team [30]. An operator may fine-tune the ECD system by adjusting voltage, electrolyte flow, and cycle time variables to ensure precise and controlled burr removal without affecting the overall dimensions of the component.

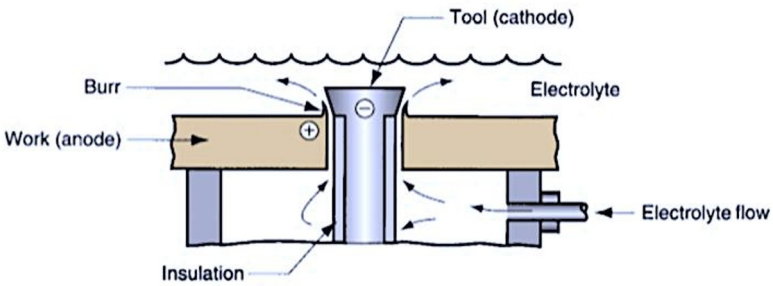

Fig. 8. Electrochemical deburring

Electrochemical deburring (ECD) offers several advantages for removing burrs from workpieces, making it a preferred process in many applications [28]. The merits of electrochemical deburring include:

1) Deburring precision: ECD excels at removing burrs that are challenging to access using conventional methods. By selectively impacting only the immediate area around the burr, ECD prevents the formation of secondary burrs and ensures high-precision deburring.
2) Design accuracy: With ECD, material removal occurs precisely at the targeted locations on the workpiece. This enables the maintenance of design accuracy, ensuring that only the necessary material is removed without compromising the overall component dimensions.

3) Enhanced component longevity: ECD helps prevent the buildup of thermal and mechanical loads on the workpiece. By avoiding excessive material removal and the generation of heat, the structural integrity and longevity of the component are preserved.
4) Increased productivity: Electrochemical deburring is a time-efficient process for burr removal compared to conventional methods. Its ability to quickly remove burrs translates into shorter production cycles and increased productivity. As a result, the overall production cost is reduced, particularly when multiple parts can be processed simultaneously.

The primary limitation of ECD is that it cannot be applied to plastics or non-conductive materials due to the reliance on electrical conductivity. While this restricts the range of materials that can be treated using ECD, it remains highly effective for metal and alloy workpieces. There are also functional limitations to consider, particularly with respect to burr length and component volume. These limitations are not strictly defined and may vary depending on the specific application. The design and layout of the fixture used in the ECD process can become complex and expensive to produce, requiring engineers to possess experience in ECD process layout and the testing of manufacturing fixtures.

3.3 Electrochemical grinding (ECG)

Electrochemical grinding (ECG) is a specialized material removal process that utilizes a negatively charged grinding wheel and an electrolyte fluid to cut through hard materials [31]. It is specifically effective on materials that have good electrical conductivity and can be positively charged, as the grinding wheel operates with a negative charge. While ECG shares similarities with electrochemical machining, the key distinction lies in the use of a grinding wheel instead of a contour-shaped tool [32]. By combining elements of both electrochemical machining and conventional grinding processes, ECG enables the precise removal of material from a workpiece. The fundamental principle of ECG revolves around electrically removing material while incorporating a negatively charged, highly abrasive grinding wheel submerged in an electrolytic fluid, with the workpiece being positively charged. This unique setup is illustrated in Figure 9. In ECG, anodic dissolution is enhanced by the conductive nature of the grinding wheel. To achieve optimal results, diamond and aluminum oxide are commonly employed as abrasives in this process [33].

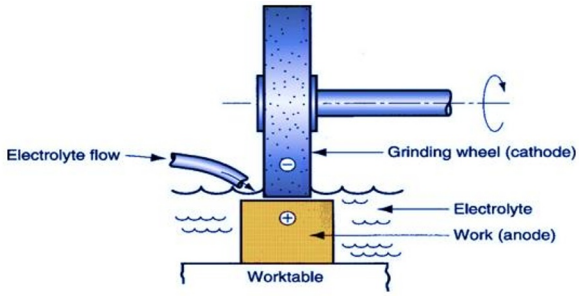

Fig. 9. Electrochemical Grinding machine

Electrochemical grinding (ECG) finds its application in scenarios where traditional machining processes are impractical or time-consuming, especially for hard metallic materials. Some notable applications of ECG include sharpening cemented carbide tools, grinding delicate parts like surgical needles and thin-wall tubes, honing honeycomb metals for aerospace purposes, and removing surface defects from parts where excessive material removal and residual stresses are undesirable, such as re-profiling locomotive gears [32,33]. ECG is particularly advantageous when dealing with materials surpassing a hardness level of 65 HRC, as it enables a removal rate up to ten times higher compared to conventional methods. Due to the minimal abrasion involved, ECG yields surfaces free from scratches, burrs, and residual stresses, making it suitable for applications like sharpening hypodermic needles, profiling vehicle gears, grinding turbine blades, refurbishing fatigue cracks in underwater structures, machining metals for aerospace vehicles, and fabricating carbide cutting tools [34].
The advantages of employing the electrochemical grinding technique in manufacturing industries are significant. They include minimal wear on the grinding wheel tool, the capability of removing up to 95% of metal, extended lifespan of the grinding wheel, the ability to machine hard materials, higher surface finish and precision tolerance compared to conventional grinding methods, negligible wear on the working tool, efficient material removal through electrochemical reactions, occurrence of abrasive forces only during film removal on the workpiece surface, and prevention of heat damage to the workpiece [34]. However, there are certain limitations to electrochemical grinding. The machine operates on a cathode and anode system, necessitating the use of negatively charged materials that match the positively charged grinding wheel. The process is applicable only to surface grinding, and the electrolytic fluid used can be corrosive to both

the workpiece and the wheel surface. Additionally, electrochemical grinding can be costlier due to its complex operation, requiring skilled and experienced personnel. The process is limited to conductive materials, and it is not suitable for grinding working pieces with cavities that are inaccessible to the grinder due to films within them. Moreover, the electrolyte submerging the workpiece may cause corrosion on the material.

4 Chemical machining (CHM) processes

CHM processes involve the use of chemical etchants to selectively remove material from workpieces. The main processes in CHM are chemical milling, chemical blanking, photochemical machining, and chemical engraving. These processes follow a series of steps including cleaning, masking, etching, and demasking. In chemical machining, cleaning is the initial step, ensuring the workpiece surfaces are uniformly prepared for etching. Masking follows, where a chemically resistant coating called a maskant is applied to protect specific areas from etching. The maskant is typically made of materials such as neoprene, polyethylene, or polyvinyl chloride. During the etching stage, the workpiece is immersed in an etchant that chemically attacks the unmasked areas, transforming the material into soluble salts (described in table 1). Once the desired material removal is achieved, the workpiece is withdrawn from the etchant and cleaned to halt the process. Demasking involves removing the maskant from the part, and various methods such as cutting and peeling, photographic resist, or screen resist can be employed for this purpose.

Table 1. Work materials and Etchants in CHM, with penetration rates and etch factors.

		Penetration Rates		
Work Material	**Etchant**	**mm/min**	**in/min**	**Etch Factor**
Aluminum and alloys	$FeCl_3$	0.020	0.0008	1.75
	NaOH	0.025	0.001	1.75
Copper and alloys	$FeCl_3$	0.050	0.002	2.75
Magnesium and alloys	H_2SO_4	0.038	0.0015	1.0
Silicon	$HNO_3 : HF : H_2O$	very slow		NA
Mild steel	$HCl:HNO_3$	0.025	0.001	2.0
	$FeCl_3$	0.025	0.001	2.0
Titanium and alloys	HF	0.025	0.001	1.0
	$HF : HNO_3$	0.025	0.001	1.0

4.1 Chemical Milling

Chemical milling is a variation of CHM that involves cutting and peeling the maskant to achieve different surface finishes. The consistency of the finish depends on the extent of penetration, and the quality deteriorates as the distance from the edge increases. Chemical milling carries minimal metallurgical risk, usually around 0.005 mm on the workpiece surface [35, 36]. The figure 10 shows the sequence of processing steps in chemical machining. (a) Clean the raw part, (b) apply the masking agent, (c) scribe, cut and peel the masking material from the areas to be etched, (d) etch, and (e) remove the masking material and clean to produce the finished part.

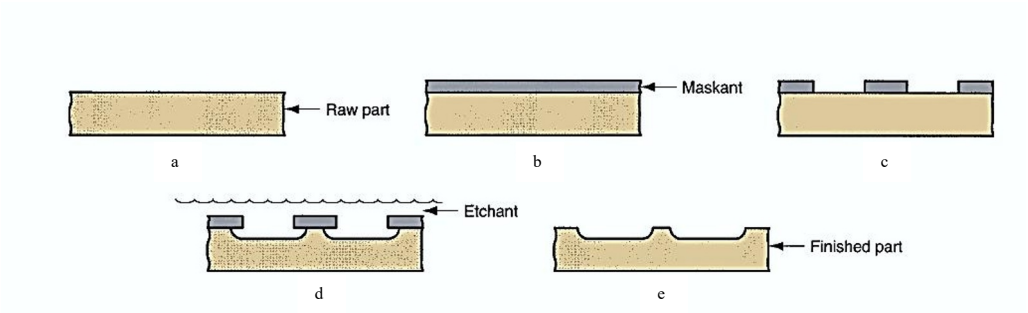

Fig. 10. Chemical milling

Table 2. Surface finishes expected in chemical milling.

Work Material	Surface Finishes Range	
	μm	μ-in
Aluminum and alloys	1.8–4.1	70–160
Magnesium	0.8–1.8	30–70
Mild steel	0.8–6.4	30–250
Titanium and alloys	0.4–2.5	15–100

4.2 Chemical Blanking

Chemical blanking provides burr-free components and can employ image resistance methods, such as photoresist or screen resistance, for masking [37]. Chemical blanking is typically limited to thin materials and complex shapes (shown in figure 11). Chemical blanking utilizes chemical oxidation to cut small sections of thin sheet metal, particularly up to 0.025 mm thick or when complex cuts are required. This is important because traditional punch and die methods may not be suitable due to damaging forces or high tooling costs.

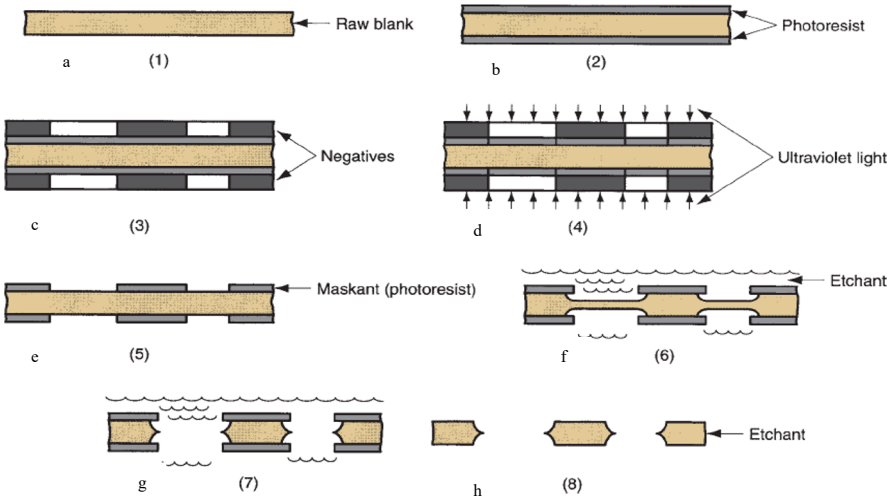

Fig. 11. Steps for chemical blanking

4.3 Photochemical machining

Photochemical machining is a form of chemical machining that utilizes a photoresist masking process [7]. Photochemical machining is widely used in the electronics industry to create intricate circuit designs on semiconductor wafers. The process involves cleaning the part, applying resist through methods like dipping or spraying, exposing it to ultraviolet light using a negative template, developing to remove resist from the areas to be etched, etching the part, and finally removing the resist to produce the finished part (figure 12). It is employed when precise tolerances and intricate patterns are required on metal parts. The photoresist masking method can also be applied in chemical blanking and chemical engraving [38].

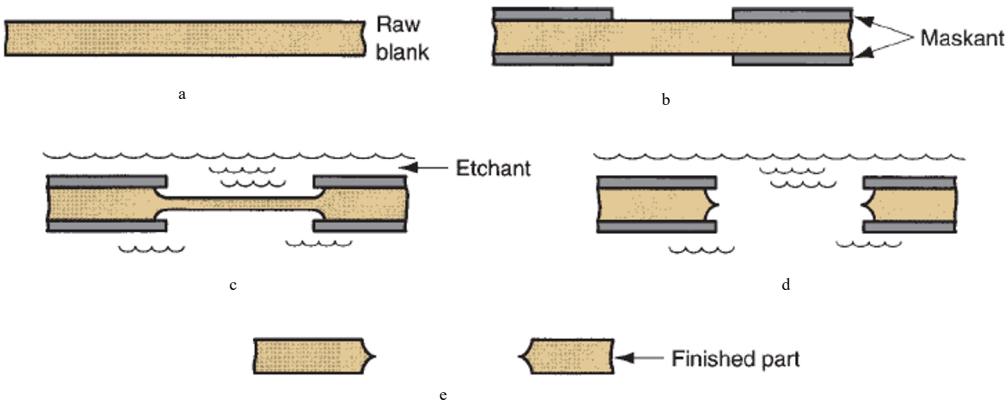

Fig. 12. Steps used in photochemical machining

4.4 Chemical Engraving

Chemical engraving, another form of chemical machining, is used to manufacture nameplates and panels with lettering or artwork [39]. It offers flexibility in creating panels with recessed or raised lettering by reversing the portions to be engraved. Masking in chemical engraving can be achieved using photoresist or screen resist methods [40]. The process is similar to other CHM methods, with the filling step preceding etching. Filling involves applying paint or a coating to the etched areas, enhancing the pattern. The panel is then soaked in a solvent that dissolves the resist but not the coating, resulting in the coating remaining in the engraved regions. Overall, the advantages of chemical machining processes include easy weight reduction, low scrap rates, cost-effectiveness, no effect on material properties, simultaneous material removal, absence of stress introduction, easy design changes, and good surface quality. However, there are challenges such as difficulty in achieving sharp corners, limitations in processing dense metals, low scribing accuracy affecting dimensional accuracy, hazardous etchants requiring careful handling, and expensive treatment of etchants [41, 42]. Moreover, concerns such as the environmental impact of chemical machining processes must address the proper handling and disposal of hazardous chemicals. Industry practices must prioritize the use of environmentally friendly chemicals, and efforts have been made to study waste etchant regeneration and recovery systems. Preventing chemical pollution of water sources is crucial to protect aquatic life and ensure water availability for human consumption. Reuse and recycling methods should also be emphasized to minimize the environmental footprint of chemical machining.

5 Thermal machining processes

Thermal machining processes refer to a group of manufacturing techniques that rely on high temperatures and thermal energy to remove material from a workpiece [43]. The primary mechanisms employed in these processes are fusion and vaporization. By subjecting the workpiece to intense heat, the material is either melted or converted into vapor, facilitating its removal. However, it is important to note that the high temperatures involved in thermal machining can result in adverse effects on the workpiece. These effects may manifest as poor surface finishes, where the final appearance and

smoothness of the machined surface may not meet desired standards [44]. Factors such as heat-induced distortion, residual stresses, and potential material degradation can contribute to the compromised surface finish. Thermal machining processes can be categorized into different types based on the specific techniques employed [43], [45]. These classifications provide a framework for understanding and distinguishing between the various methods used in thermal machining. By classifying these processes, it becomes easier to comprehend their unique characteristics, applications, and operational principles.

5.1 Oxyfuel-cutting processes

Oxyfuel cutting utilizes the heat generated by the combustion of gases along with oxygen [46]. A cutting torch delivers a carefully controlled mixture of fuel gas and oxygen to the work surface. The gases commonly employed in this process include propane, propylene, MAPP, and acetylene.

5.2 Electric Discharge (ED) Machining

ED machining involves the use of oppositely charged electrons to remove material at high temperatures, reaching a point where the metal can be melted or vaporized [47, 48]. The setup and a close-up view of the gap are depicted in Figure 13, a. The surface finish achieved in EDM is directly proportional to the discharge frequency. Figure 13, b illustrates the relationship between surface finish and discharge current for both low and high frequencies. Wire EDM, which employs a wire electrode controlled by CNC, is particularly useful for creating precise cuts, such as those needed for fabricating punches and dies [49].

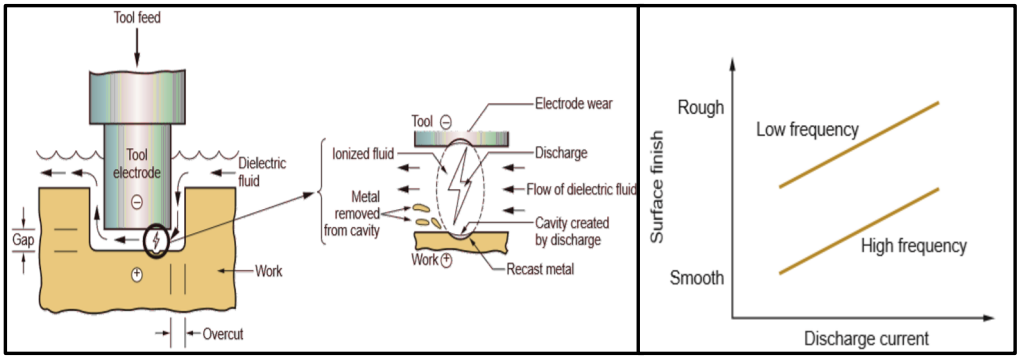

Fig. 13. Electric discharge machining and the gap

5.3 Electron beam machining

Electron beam machining employs a high-speed stream of electrons focused on the work-piece surface to remove material through vaporization and/or melting [50]. The electrons travel at approximately 75 percent of the speed of light, and an electromagnetic lens is used to concentrate the beam onto the work-piece [51, 52]. Figure 14 provides a schematic representation of the electron beam machining mechanism.

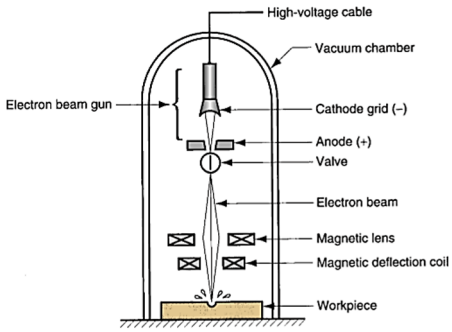

Fig.14. Electron beam machining

5.4 Laser Beam (LB) Machining

LB machining involves the removal of material through vaporization and ablation using a laser light source. This process is capable of machining various materials, including plastics, wood, and metals. It finds applications in drilling, slitting, slotting, and scribing [52]. Additionally, LB machining can achieve nanomachining capabilities, as shown in Figure 15.

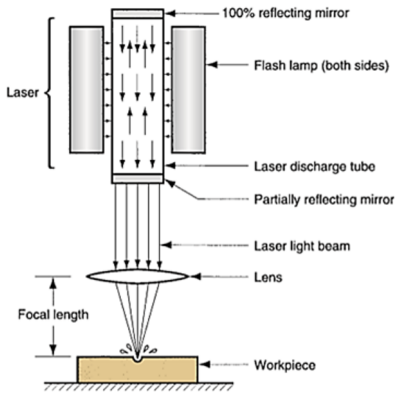

Fig. 15. Laser beam machining

5.5 Arc cutting

Arc cutting is a broad category that encompasses various techniques, and one notable method within this group is plasma arc cutting as depicted in Figure 16 [53]. This particular approach harnesses the power of superheated and electrically ionized gas to melt and process metals effectively [54]. Operating at temperatures ranging from 18,000°F to 25,000°F, plasma arc cutting utilizes the intense heat generated by the electrically ionized gas to facilitate the metal cutting process. During plasma arc cutting, a gas is ionized by an electrical arc, creating a superheated plasma state. This plasma is then directed towards the work surface, where it interacts with the metal, causing it to melt. The molten metal is subsequently blown away by a high-velocity gas stream, resulting in the removal of material [54, 55]. The key advantage of plasma arc cutting lies in its ability to attain extremely high temperatures, surpassing the melting point of most metals.

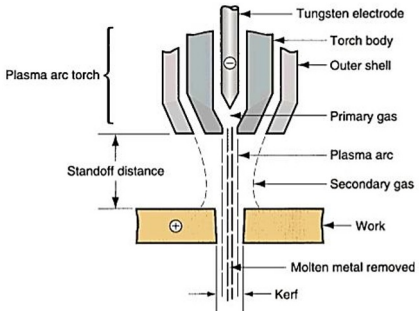

Fig. 16. Plasma arc machining

Plasma arc cutting offers versatility in terms of the materials it can process. It is capable of cutting a wide range of metals, including steel, stainless steel, aluminum, and copper. Furthermore, plasma arc cutting is often preferred for its ability to achieve clean and accurate cuts, minimizing the need for subsequent finishing operations. The controlled application of superheated plasma provides a reliable and efficient means of metal cutting. The intense heat generated by the electrically ionized gas enables rapid material removal, making plasma arc cutting suitable for applications that require high cutting speeds and precision.

6 Insight and outlook

6.1 Insight from the Research

The research on non-traditional machining techniques has provided valuable insights into their operational aspects, outcomes, and significance in the manufacturing industry. Through a deductive and qualitative approach, this study has shed light on the potential benefits and challenges associated with these techniques.

One key insight gained from the research is the importance of staying abreast of technological advancements in non-traditional machining. As new processes and methodologies emerge, manufacturers need to continuously update their knowledge and skillsets to effectively meet design requirements and enhance productivity. By embracing these advancements, companies can gain a competitive edge in the market and explore new avenues for innovation.

Another significant finding is the diverse range of applications for non-traditional machining techniques. From mechanical energy-efficient processes to electrochemical, chemical, and thermal machining, each approach offers unique advantages and limitations. Understanding these differences allows manufacturers to choose the most suitable technique for specific applications, whether it's achieving intricate shapes, improving surface finish, or enhancing production efficiency.

Additionally, the research has highlighted the environmental considerations associated with non-traditional machining processes. While these techniques offer numerous benefits, such as reduced material waste and enhanced precision, it is crucial to address the potential environmental impact, particularly in chemical machining. Developing effective alternatives to chemicals and implementing sustainable practices can help mitigate any adverse effects on the environment.

6.2 Outlook for Future Development

The research on non-traditional machining techniques opens up exciting opportunities for future development and advancements in the field. Several areas warrant further investigation to enhance the understanding and application of these techniques in the manufacturing industry.

Firstly, exploring the integration of non-traditional machining techniques with emerging technologies, such as additive manufacturing (3D printing) and automation, holds great potential. Combining these techniques can lead to more efficient and precise manufacturing processes, enabling the production of complex components with improved accuracy and reduced lead times.

Moreover, there is a need to investigate the economic feasibility of implementing non-traditional machining techniques on a larger scale. Analyzing the cost-effectiveness and return on investment of these techniques, considering factors such as energy consumption, equipment requirements, and skilled labor, can provide valuable insights for decision-makers in the manufacturing sector.

Additionally, the research outlook should include further studies on the optimization of non-traditional machining parameters and process parameters. Fine-tuning these variables can lead to improved efficiency, reduced cycle times, and enhanced surface quality. Exploring advanced modelling and simulation techniques to predict the behaviour of non-traditional machining processes can also contribute to process optimization and provide a deeper understanding of the underlying mechanisms.

Lastly, the research outlook should emphasize collaboration between academia, industry, and government bodies to foster innovation and knowledge sharing. Encouraging partnerships and knowledge exchange platforms can accelerate the adoption of non-traditional machining techniques and drive continuous improvement in the manufacturing sector.

By embracing these research directions and leveraging the insights gained from this study, the manufacturing industry can unlock the full potential of non-traditional machining techniques, leading to increased productivity, improved product quality, and sustainable manufacturing practices.

7 Conclusion

In this research, a comprehensive investigation was conducted on various non-traditional machining processes, including mechanical, electrochemical, chemical, and electrical energy cutting methods. The primary objective was to gain a thorough understanding of these processes, and through detailed discussions, this objective was successfully achieved.
Non-traditional machining is an industry that continues to grow with constant advancements and innovations. However, it is important to recognize that it will never completely replace traditional machining methods that have served us well for many years. While non-traditional machining allows us to manufacture complex parts that were previously challenging, traditional machining techniques such as milling, turning, and drilling will always be more cost-effective for simpler shapes and designs.
Both non-traditional and traditional machining methods hold equal importance in meeting our design requirements. Regardless of which method plays a major role in the manufacturing industry, they complement each other. It is worth noting that most non-traditional machining methods consume significant amounts of energy, either to achieve high temperatures or generate sufficient pressure for machining operations. This energy consumption adds to the production cost. From an economic perspective, it is impractical to disregard traditional machining due to its simplicity, lower production costs, and the ability to be operated by less skilled workers. However, traditional machining has limitations in terms of design possibilities. The production rate is also a crucial factor to consider when deciding between the two methods.

As technology advances, new non-traditional machining methods are developed to meet the design requirements of innovative products. Consequently, there will always be a place for non-traditional machining in the manufacturing industry. One key aspect of electrochemical deburring is the influence of machining speed, electrolyte temperature, and applied voltage. These factors directly affect the electrochemical reactions responsible for deburring. Sharp edges on burrs accelerate the deburring process as more electrons gather in those areas compared to other parts. The deburring rate decreases as the burrs dissolve or are removed, resulting in fewer electrons at the edges. Increasing the rotational speed enhances the uniformity of the electrochemical reaction. In summary, electrochemical deburring proves to be efficient and effective in removing burrs from metal surfaces compared to conventional deburring methods.

The research conducted in this study demonstrated that chemical machining processes offer a wide range of advantages with minimal disadvantages. Chemical machining is commonly employed in the manufacturing of intricate device parts for various applications and decorative items. To ensure the desired structures are produced, it is crucial to execute the machining process with great care. Environmental regulations play a significant role when utilizing chemical machining techniques. Continuous implementation and enforcement of environmental laws are essential for chemical machining of tool parts. Through further research, effective alternatives to chemicals used in chemical processes can be developed and improved.

References

1. O. Peter, A. Pradhan, and C. Mbohwa, “Industry 4.0 concepts within the sub–Saharan African SME manufacturing sector,” *Procedia Comput. Sci.*, vol. 217, pp. 846–855, 2023.

2. L. Da Xu, E. L. Xu, and L. Li, "Industry 4.0: state of the art and future trends," *Int. J. Prod. Res.*, 2018.

3. O. M. Ikumapayi, E. T. Akinlabi, P. Onu, and O. P. Abolusoro, "Rolling operation in metal forming: Process and principles – A brief study," *Mater. Today Proc.*, 2020.

4. J. Ma, J. D. Harstvedt, D. Dunaway, L. Bian, and R. Jaradat, "An exploratory investigation of Additively Manufactured Product life cycle sustainability assessment," *J. Clean. Prod.*, 2018.

5. G. Zuccaro *et al.*, "Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall," *Autom. Constr.*, 2019.

6. K. P. Rajurkar, H. Hadidi, J. Pariti, and G. C. Reddy, "Review of Sustainability Issues in Non-Traditional Machining Processes," *Procedia Manuf.*, 2017.

7. O. M. Ikumapayi, E. T. Akinlabi, and P. Onu, "Emerging trend in forging operation," in *Lecture Notes in Mechanical Engineering*, 2020.

8. B. Ahuja, M. Karg, and M. Schmidt, "Additive manufacturing in production: challenges and opportunities," in *Laser 3D Manufacturing II*, 2015.

9. H. Zhou, J. Zhang, D. Yu, P. Feng, Z. Wu, and W. Cai, "Advances in rotary ultrasonic machining system for hard and brittle materials," *Advances in Mechanical Engineering*. 2019.

10. M. Asmael, B. Safaei, Q. Zeeshan, O. Zargar, and A. A. Nuhu, "Ultrasonic machining of carbon fiber–reinforced plastic composites: a review," *International Journal of Advanced Manufacturing Technology*. 2021.

11. J. Singh, C. Singh, and K. Singh, "Rotary ultrasonic machining of advance materials: A review," *Mater. Today Proc.*, 2023.

12. P. K. S. C. Fernando, M. Zhang, and Z. Pei, "Rotary ultrasonic machining of rocks: An experimental investigation," *Adv. Mech. Eng.*, 2018.

13. D. Cui *et al.*, "Applications of Water Jet Cutting Technology in Agricultural Engineering: A Review," *Applied Sciences (Switzerland)*. 2022.

14. G. M. Bazenov, G. T. Itybaeva, A. Z. Kasenov, and A. S. Yanyushkin, "Water-Jet Cutting of Glass Sheet," *Russ. Eng. Res.*, 2022.

15. F. Bañon, A. Sambruno, L. González-Rovira, J. M. Vazquez-Martinez, and J. Salguero, "A review on the abrasive water-jet machining of metal–carbon fiber hybrid materials," *Metals*. 2021.

16. T. S. Nanjundeswaraswamy and A. Professor, "A Literature Review on Parameters Influencing Abrasive Jet Machining and Abrasive Water Jet Machining," *Varun R J. Eng. Res. Appl. www.ijera.com*, 2019.

17. Y. Natarajan, P. K. Murugesan, M. Mohan, and S. A. Liyakath Ali Khan, "Abrasive Water Jet Machining process: A state of art of review," *Journal of Manufacturing Processes*. 2020.

18. R. Melentiev and F. Fang, "Recent advances and challenges of abrasive jet machining," *CIRP Journal of Manufacturing Science and Technology*. 2018.

19. S. Madhu and M. Balasubramanian, "Challenges in abrasive jet machining of fiber-reinforced polymeric composites – a review," *World Journal of Engineering*. 2021.

20. A. Goyal, H. Singh, R. Goyal, R. Singh, and S. Singh, "Recent advancements in abrasive flow machining and abrasive materials: A review," *Mater. Today Proc.*, 2022.

21. N. Dixit, V. Sharma, and P. Kumar, "Research trends in abrasive flow machining: A systematic review," *Journal of Manufacturing Processes*. 2021.

22. B. Azarhoushang, "Abrasive Machining Processes," in *Tribology and Fundamentals of Abrasive Machining Processes: Third Edition*, 2021.

23. J. Li, L. Yang, W. Liu, X. Zhang, and F. Sun, "Experimental research into technology of abrasive flow machining nonlinear tube runner," *Adv. Mech. Eng.*, 2014.

24. A. D. Oza, A. Goyal, V. Buch, and M. Kumar, "Electrochemical discharge machining process: A review on process parameters and future scope," *Mater. Today Proc.*, 2022.

25. P. Kaewsaard, H. Zhu, H. Qi, and V. Tangwarodomnukun, "Laser surface masking of stainless steel for electrochemical machining process," *Int. J. Adv. Manuf. Technol.*, 2021.

26. H. Sohrabpoor, S. P. Khanghah, S. Shahraki, and R. Teimouri, "Multi-objective optimization of electrochemical machining process," *Int. J. Adv. Manuf. Technol.*, 2016.

27. F. Klocke, S. Harst, L. Ehle, M. Zeis, and A. Klink, "Surface integrity in electrochemical machining processes: An analysis on material modifications occurring during electrochemical machining," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, 2018.

28. S. P. Kadam and S. Mitra, "Electrochemical deburring - A comprehensive review," in *Materials Today: Proceedings*, 2021.

29. T. He, S. Huang, S. Fang, H. Deng, Q. Ding, and M. Zhang, "Study on the Electrochemical Deburring for the External Surface of the Microhole Caused by Mechanical Drilling Process," *Machines*, 2022.

30. S. J. Lee, C. P. Liu, T. J. Fan, and Y. H. Chen, "Deburring miniature components by electrochemical method," *Int. J. Electrochem. Sci.*, 2013.

31. K. Fan, Z. Jin, and X. Zhu, "Investigation on electrochemical grinding (ECG) of pure iron material," *Int. J. Adv. Manuf. Technol.*, 2022.

32. F. Jiao, X. Ma, W. Bie, Y. Niu, and S. Niu, "Research Status and Prospects of Electrochemical Grinding Technology," *Binggong Xuebao/Acta Armamentarii*. 2022.

33. H. M. Yehia, M. Hakim, and A. El-Assal, "Effect of the Al2O3 powder addition on the metal removal rate and the surface roughness of the electrochemical grinding machining," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, 2020.

34. Y. C. Ge, Z. Zhu, D. Wang, Z. Ma, and D. Zhu, "Study on material removal mechanism of electrochemical deep grinding," *J. Mater. Process. Technol.*, 2019.

35. J. Wang *et al.*, "Research Status and Prospect of Laser Scribing Process and Equipment for Chemical Milling Parts in Aviation and Aerospace," *Micromachines*. 2022.

36. V. Deshmukh, R. Kadam, and S. S. Joshi, "Removal of alpha case on titanium alloy surfaces using chemical milling," *Mach. Sci. Technol.*, 2017.

37. C. Owusu, S. Mensah, K. Ackah, and R. K. Amankwah, "Reducing preg-robbing in carbonaceous gold ores using passivative or blanking agents," *Miner. Eng.*, 2021.

38. A. Koyuncuoğlu, D. Işık Akçakaya, Ö. Şardan Sukas, and H. Külah, "Wet etching of platinum (Pt) electrodes for piezoelectric transducers using a thick photoresist mask," *Micro Nano Eng.*, 2022.

39. Z. Bassyouni and J. D. A. Ziki, "The capabilities of spark-assisted chemical engraving: A review," *J. Manuf. Mater. Process.*, 2020.

40. G. Francis, B. W. Stuart, and H. E. Assender, "Selective ozone treatment of PDMS printing stamps for selective Ag metallization: A new approach to improving resolution in patterned flexible/stretchable electronics," *J. Colloid Interface Sci.*, 2020.

41. L. A. Hof and R. Wuthrich, "Glass precision micro-cutting using spark assisted chemical engraving," *Adv. Ind. Manuf. Eng.*, 2021.

42. J. D. Abou Ziki and R. Wüthrich, "Nature of drilling forces during spark assisted chemical engraving," *Manuf. Lett.*, 2015.

43. M. Gostimirovic, P. Kovac, and M. Sekulic, "An inverse heat transfer problem for optimization of the thermal process in machining," *Sadhana - Acad. Proc. Eng. Sci.*, 2011.

44. B. Bhattacharyya and B. Doloi, "Machining processes utilizing thermal energy," in *Modern Machining Technology*, 2020.

45. N. Ben Salah, F. Ghanem, and K. Ben Atig, "Numerical study of thermal aspects of electric discharge machining process," *Int. J. Mach. Tools Manuf.*, 2006.

46. C. R. Martin, A. Untaroiu, K. Xu, and S. M. M. Raman, "A Study of the Efficacy of Flame Electrical Resistance for Standoff Measurements During the Oxyfuel Cutting Process," *J. Manuf. Sci. Eng.*, 2022.

47. S. Deepthi and B. V. Dharmendra, "A review of current research on powder mixed electric discharge machining," *Int. J. Mech. Prod. Eng. Res. Dev.*, 2019.

48. C. Prakash, H. K. Kansal, B. S. Pabla, S. Puri, and A. Aggarwal, "Electric discharge machining - A potential choice for surface modification of metallic implants for orthopedic applications: A review," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. 2016.

49. N. Gurusamy, J. Natarajan, and P. K. Palaniappan, "Parameter optimization of the CNC wire-cut edm process for machining aluminium 6063-B4C metal matrix composites," *Trans. Famena*, 2019.

50. M. S. Amalnik, "Intelligent knowledge based system for material processing by electron beam machining (EBM) process," *Int. J. Adv. Eng. Technol.*, 2017.

51. H. E. Joe, E. G. Kang, and M. B. G. Jun, "A review of state of the art of electron beam and ion beam machining," *J. Korean Soc. Precis. Eng.*, 2018.

52. S. M. Scott and Z. Ali, "Fabrication methods for microfluidic devices: An overview," *Micromachines*. 2021.

53. J. Kechagias, M. Petousis, N. Vidakis, and N. Mastorakis, "Plasma Arc Cutting Dimensional Accuracy Optimization employing the Parameter Design approach," *ITM Web Conf.*, 2017.

54. S. S. Pawar and K. H. Inamdar, "Factors affecting quality of plasma arc cutting process: A review," *Int. J. Adv. Technol. Eng. Sci.*, 2016.

55. A. Klimpel *et al.*, "Experimental investigations of the influence of laser beam and plasma arc cutting parameters on edge quality of high-strength low-alloy (HSLA) strips and plates," *Int. J. Adv. Manuf. Technol.*, 2017.