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A COMPREHENSIVE REVIEW OF CONVENTIONAL AND NON-CONVENTIONAL MACHINING PROCESSES FOR ADVANCED MANUFACTURING APPLICATIONS

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ABSTRACT

The growing need for sophisticated materials and high-precision components has brought attention to how crucial effective and sustainable machining techniques are to contemporary manufacturing. The operating principle, applications, benefits, and drawbacks of both conventional and non-traditional machining techniques are outlined in this review study. In addition to non-conventional techniques including electrical discharge machining, laser beam machining, electrochemical machining, ultrasonic machining, water jet machining, and plasma arc machining, the traditional processing techniques like turning, milling, drilling, and grinding are examined. Material removal, surface quality, dimensional accuracy, tool wear, energy consumption, cost, and process efficiency are all examined and contrasted. They are also covered in the manufacturing sectors of electronics, biomedical, automotive, and aerospace, with a focus on the machining of complex and challenging-to-cut materials. Furthermore, the review highlights the importance of hybrid machining technologies, automation, artificial intelligence, and energy-efficient manufacturing strategies in improving productivity and reducing environmental impacts. The study highlights that the selection of suitable machining process: should be based on material properties, part geometry, quality requirement, and economical factors. Overall, it gives an idea of the capabilities and challenges of various machining technologies and future research directions to realize a precision, cost-effective and sustainable advanced manufacturing.

Keywords: Conventional machining, non-conventional machining, Advanced manufacturing, Material removal rate, Hybrid machining, Sustainable manufacturing, Machining efficiency.

1. INTRODUCTION

Machining processes are key tools in the manufacturing industry as they are used to create components of a specific dimension, geometry, and surface quality. As a result of the development of industrial technologies, more and more high precision components are in demand in various engineering areas such as aerospace, automotive, biomedical, electronics, and others [1]. The traditional machining technologies like turning, milling, drilling, and grinding are still extensively employed due to the reliability, flexibility and industrial applications.

However, there are some drawbacks to conventional machining processes, particularly when working with hard materials, complex shapes and advanced alloys. Non-traditional machining techniques as electrochemical, ultrasonic, water jet, laser beam, and electrical discharge machining have emerged as a result of the issues [2]. They entail the use of mechanical, electrical, thermal, or chemical energy to remove material and improve cutting capabilities for the production of intricate parts and the machining of materials that are challenging to cut.

Numerous aspects, including material qualities, material removal rate, dimensional accuracy, surface finish, tool wear, energy consumption, and production cost, influence the choosing of the best machining technique. Therefore, in order to choose the best machining process for the different industrial needs, it is essential to have a comparative understanding of conventional and non-conventional machining methods [3]. Additionally, new technologies like hybrid machining, automation and artificial intelligence are opening new possibilities for enhancing the efficiency, precision and sustainability of machining.

The conventional and non-conventional machining processes are summarised in this review paper in terms of their working principles, merits, demerits, applications and comparison of their performances in advanced manufacturing [4]. It also looks at recent technological developments, the gaps in existing studies, and the areas for future research to help in the selection and optimization of machining processes to provide efficient, economical, and sustainable manufacturing.

2. CONVENTIONAL MACHINING PROCESSES

Conventional machining processes are one of the most common manufacturing technologies used to create parts to specific dimensions, shape and surface finish. These processes are usually based on the relative movement of a cutting tool and the workpiece to remove unwanted material from the workpiece [5]. Mechanical action: material is

removed by cutting into the material causing the creation of chips. In industries like automotive, aerospace, construction, machinery and general engineering, conventional machining is widely employed for producing metallic and non-metallic components. Conventional machining methods, which include turning, milling, drilling, and grinding, are common machining techniques used for a variety of manufacturing applications.

The efficiency of traditional machining depends on a number of factors, including cutting speed, feed rate, depth of cut, tool shape, workpiece hardness, and cutting fluid application. The right choice of these parameters contributes to increase of productivity, dimensional accuracy, surface quality and tool life [6]. While the traditional machining methods are proven and relatively low cost for most applications, there are limitations with such processes when using highly hard materials, complex geometries and those that are heat sensitive. However, they are versatile, readily available, and are compatible with computer numerical control (CNC) systems, which is why they are vital to modern manufacturing operations.

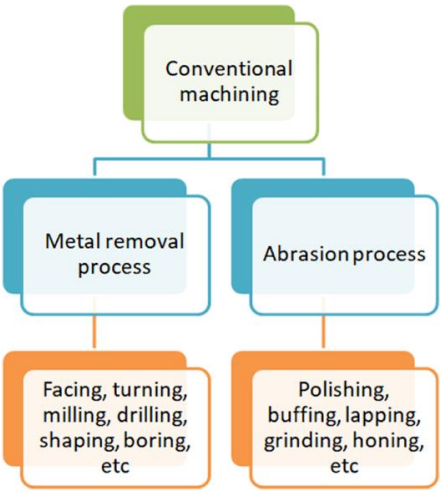


Figure 1: Conventional Machining [7].

2.1. Turning, Milling, Drilling and Grinding

The principal conventional machining processes in the manufacture of parts having precise shapes, sizes, and surface finishes are turning, milling, drilling, and grinding. Turning is used to make cylindrical parts, milling is used to make flat parts, slots, and complex shapes by rotating the tool against the part. The drilling process is used to create circular holes by rotating and moving a drill bit along a specific axis, while the grinding process uses abrasive materials to achieve high dimensional accuracy and a good surface finish [8]. These processes are used widely in the automotive, aerospace, electronics and precision engineering industries. The performance they provide is influenced by cutting parameters, tool material and tools, work piece properties, and cooling conditions and therefore, proper selection of the cutting process is critical in order to increase productivity, minimize tool wear, and meet the needed quality specifications required in advanced manufacturing applications.

❖ Turning

Turning is a conventional manufacturing process applied to cylindrical, conical and rotationally symmetrical parts. During this process the work piece rotates about its axis while a cutting tool is fed across its surface, to remove unwanted material. It is usually performed on a lathe machine and may comprise of the following operations: facing, taper turning, threading, grooving and boring. Turning performance is influenced by the following factors: cutting speed, feed rate, depth of cut, tool geometry and work material. The selection of these parameters can enhance dimensional accuracy, surface finish, tool life, decrease excessive heat generation and tool wear [9].

Turning is a very common process for manufacturing shafts, bolts, pins, bushings, threaded parts and automotive engine parts. Today's CNC turning centres improve productivity and accuracy by automating the movement of tools and by providing repeatable machining operations. Turning offers a number of significant benefits: production efficiency, dimensional stability and batch and mass production. But it can be used mostly for parts that can be easily held and turned for machining.

❖ **Milling**

In milling, material is removed from a workpiece by cutting it with a spinning multipoint cutting tool. Face milling, end milling, slot milling, profile milling, and contour milling are a few popular milling techniques used to produce complex forms, grooves, pockets, and flat surfaces. Cutting speed, feed rate, depth of cut, tool shape, and workpiece qualities are the variables that influence milling performance. By using an appropriate cutting parameter and tool selection, vibration, tool wear and surface defects can be minimized, and the machining accuracy becomes better [10].

Common applications include aerospace structures, automotive components, moulds and dies, machine frames and precision engineering products. CNC milling machine and multi axis machining centre can be used to manufacture complex parts with high accuracy and less manual work. The process is very versatile and can be used for roughing as well as finishing processes. But high tooling costs, vibration, and complex process planning can pose problems, especially when working on very complicated parts or with difficult materials.

❖ **Drilling**

Drilling is a traditional manufacturing method of creating circular holes in solid materials. It includes the action of rotating a drill bit and pushing it into the work to chip away to form a hole of a given diameter and depth. Examples of common operations are through-hole drilling, blind hole drilling, deep hole drilling, and step drilling. Other processes like reaming, tapping, countersinking and counterboring can be used to increase hole precision or to prepare holes for fasteners. The spindle speed, feed rate, drill geometry, workpiece hardness, cooling, and the efficiency of chip removal is involved in drilling quality [11].

In the automotive sector, aircraft structures, construction machinery, electronic enclosures, and all other mechanical components are all commonly drilled. Very important in the making of holes for bolts, rivets, screws and fluid passages. It is relatively cheap, fast and can be used on a large-scale. However, if the cutting conditions are not set correctly, then the following problems can occur: Burrs, tool breakage, surface quality issues, dimensional errors. These can be made quite small or exceptionally deep in hard materials, or exceedingly precise, necessitating special drilling techniques or non-conventional machining processes.

❖ **Grinding**

Grinding is an abrasive cutting process mainly applied to finish, correct dimensions and to obtain high finish. The material is cut away by a spinning grinding wheel with tiny cutting edges of abrasive particles. Common abrasives include diamond, silicon carbide, cubic boron nitride, and aluminium oxide. Grinding can be done in four different ways: surface, cylindrical, centre less, and internal. A number of factors, including dressing conditions, abrasive particle size and type, feed rate, depth of cut, and grinding wheel speed, affect the grinding process. Using coolant and choosing the right wheels can cut down on heat production and preserve surface integrity [12].

The key applications for grinding are bear-making, gear manufacturing, the production of cutting tools, automotive shafts, precision moulds, and hardened machine parts. The main benefits are that it has high dimensional accuracy, a good surface finish and it can be used to process hard materials that are hard to machine with traditional cutting tools. The use of grinding however can lead to high energy consumption, low material removal rate in finishing and potential thermal damage if process parameters are not controlled. It is especially beneficial in higher precision manufacturing processes where surface quality and reliability are critical factors.

2.2. Working Principles and Applications

Conventional machining processes rely on the contact between a cutting tool or abrasive material and the material to be cut. They all share the goal of the removal of unwanted material to achieve the desired geometry, dimensions, surface properties of the component. But for various types of motion, cutting process and tool geometry, working principle is different [13]. Turning is primarily accomplished by rotating the workpiece, milling is accomplished by rotating a multi-edge cutter, drilling is accomplished by rotating an axis which penetrates the workpiece, grinding is accomplished by using an abrasive. It is important to know these differences to choose the best process for a specific manufacturing need.

Turning is a process in which the work is held in a chuck and rotated to provide the main cutting force, and the cutting tool is fed in a controlled direction to create the cut. This arrangement can be used to create cylindrical surfaces, threads, tapers and rotational profiles. The material removal in milling occurs through a series of cutting edges on a rotating cutter which can remove material in multiple directions [14]. This makes milling suitable for

flat surfaces, slots, pockets or complex contours. Both processes can be carried out from CNC machines to guarantee repeatability, and produce more complex components with minimal manual effort.

Drilling is a process that involves rotating a drill in combination with pushing into the material being drilled. The cutting lips used on the drill remove material and the flutes carry chips away from the zone of cutting. This is a necessary process for any place where precisely located holes need to be made for assembly, fastening, lubrication or fluid movement. The opposite is grinding; this uses abrasives to scour small chips of material from the surface. It is well suited for the finishing of hardened parts and high dimensional accuracy [15], because of its working principle. While both processes can be used on a wide variety material, the selection of a process depends on the capability of the tool, heat generated from the operation and the quality of the finished product.

The industrial use of conventional machining processes is representative of their complementary roles in manufacturing. Turning is typically employed for manufacture of shafts, axles, pins and threaded parts; when machine parts, dies, moulds and complex structural features are to be made, milling is preferred; drilling is needed to make holes in mechanical assemblies, aircraft components and industrial equipment; grinding is used extensively for the precision finishing of bearings, gears and hardened surfaces. These operations are often performed in series for the purpose of attaining the appropriate quality for the components in many production systems [16]. For instance, a shaft might be initially turned to a rough size, then keyways might be milled and holes drilled in the required locations, and finally the final diameter and surface finish is obtained through grinding.

The combination of traditional manufacturing with CNC, computer-aided manufacturing (CAM), robotics and automated inspection have greatly enhanced manufacturing accuracy and productivity. Modern machining centres are capable of multiple operations, with one set-up which reduces the handling time, and lessens positioning errors. Further, real-time monitoring of cutting forces, vibration, temperature and tool wear allows for optimization of processes and predictive maintenance [17]. But conventional machining might not be the best option for very hard, brittle, fragile or heat-sensitive materials, or for some complex micro features. Consequently, advanced manufacturing applications have turned to the use of non-conventional and hybrid machining processes in addition to conventional machining.

3. NON-CONVENTIONAL MACHINING PROCESSES

Non-conventional machining processes are the latest techniques in the field of material removal which are unable to perform the same operations as the conventional machining processes, especially for hard and brittle materials, heat sensitive materials and difficult-to-machine materials. Electrical, thermal, chemical, electrochemical, or high energy fluid processes mechanically remove material from the workpiece in non-conventional procedures [18]. The techniques are particularly useful in producing parts that feature complex geometries, micro-features, tight tolerances and narrow cavities. The other major non-conventional machining processes are electrical discharge machining (EDM), laser beam machining (LBM), electrochemical machining (ECM), ultrasonic machining (USM), water jet machining (WJM) and plasma arc machining (PAM).

Choices of a suitable non-conventional machining process are determined by the electrical conductivity, hardness, brittleness, thermal sensitivity, geometry, surface quality, material removal rate and cost of the part. These processes have several benefits, such as less force is required for mechanical cutting, more complex shapes can be produced and the materials can be more difficult to cut with the conventional processes [19]. Not all of them, however, can involve high equipment costs, a great deal of energy, special operating conditions or environmental problems. They have broadened their application into advanced manufacturing sectors with the integration of computer numerical control (CNC), automation, and hybrid manufacturing technologies.

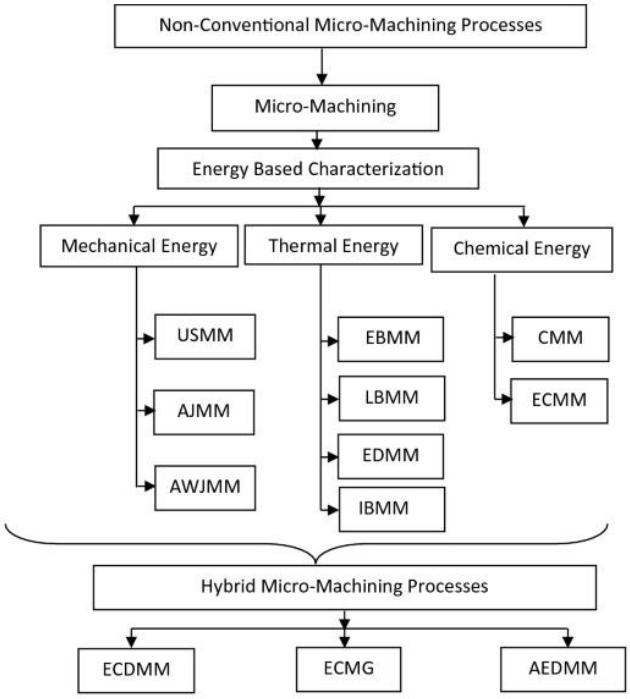


Figure 2: Non-Conventional Micro Machining Process [20].

3.1. Electrical Discharge Machining (EDM) and Laser Beam Machining (LBM)

EDM, removes material from electrically conductive workpieces through electrical sparks, allowing hard materials and complex shapes to be machined. LBM is capable of high precision cutting, drilling or shaping materials with a focused laser beam [21]. The two processes are generally used in the aerospace, automotive, and electronics industries, but EDM can only be used for conductive materials, while LBM could damage materials due to heat.

❖ **Electrical Discharge Machining (EDM)**

EDM is a thermal machining technique that uses regulated electrical discharges between an electrode and a workpiece—a substance that conducts electricity—to extract material. Both components are separated during operation by a gap that is filled with a dielectric fluid. If a proper voltage is used, repeated electrical sparks create high localized heat and the material (in small amounts) is melted and vaporized. The dielectric is used to regulate the discharge, to cool the cutting area and to flushing eroded particles out of the work zone. Additionally, EDM eliminates the need for direct tool-to-workpiece contact, which is particularly useful when treating complex and difficult conductive materials [22].

The variables influencing EDM performance include discharge current, voltage, electrode material, dielectric fluid, pulse-on and pulse-off times, and flushing conditions. Common varieties include wire EDM, hole drilling EDM, and die sinking EDM. While wire EDM uses a thin wire electrode that continuously cuts through the material to achieve the exact shape, die-sinking EDM is used to create cavities and intricate shapes. The key areas of application for EDM are aerospace components, injection moulds, dies, turbine components and precision tooling fabricated from hardened steels, super alloys and other conductive materials. It has the main merits of low mechanical cutting forces, high geometric flexibility and the ability to machine the material regardless of their conventional cutting hardness. It is only applicable to an electrically conductive material, however, and can generate recast layers, heat-affected regions, wear on the electrode and relatively low material removal rates under certain circumstances.

❖ **Laser Beam Machining (LBM)**

Laser beam machining is a process of removing material from a part by heating, melting, vaporizing or ablating it with a highly concentrated laser beam. A laser beam is created by the laser source, and then sent through an optical system to focus the beam on a point at the surface of the material. This can result in localized heating, which means that narrow cuts, small holes, and intricate patterns can be created. The material removal process can be by melting and ejecting the melt, vaporization, or other types of ablations depending on the material and the laser parameters.

It is a non-cutting process that does not have to be in contact with the workpiece, hence it can process fine and complex features with minimal mechanical loading [23].

Laser power, laser wavelength, pulse duration, beam quality, focal position, scanning speed, and optical and thermal properties related to the material are important factors that affect the effectiveness of LBM. The selection of the continuous wave or pulsed lasers will depend on the cutting, drilling, marking or micromachining application. LBM is widely employed in the aerospace industry, auto industry, electronics, medical devices, and precision sheet metal industries. It has several key benefits such as high-speed processing, narrow kerfs, flexibility and the ability to produce complex features. However, heat-affected zones, recast material, thermal distortion or surface oxidation may occur during laser machining, especially for heat sensitive materials. Other factors in industrial applications include the cost of equipment, energy usage, and laser safety issues.

3.2. Electrochemical Machining (ECM) and Ultrasonic Machining (USM)

Electrochemical Machining (ECM) is a process of controlled electrochemical dissolution, which can be employed for the removal of material from electrically conductive workpieces to obtain complex shapes and precision parts [24]. In Ultrasonic Machining (USM), the machining is achieved with the vibration of a tool at high frequencies and with the help of abrasive particles that are used to machine hard, brittle materials like glass and ceramics. Both are useful in the manufacturing of aerospace, biomedical and electronics. But it is important to manage the electrolyte when using ECM and it may be slower material removal and abrasive wear when using USM.

❖ Electrochemical Machining (ECM)

A controlled anodic dissolving technique is used in electrochemical machining, a non-traditional method that follows electrochemical principles to remove material. The work piece is the anode and the shaped tool is the cathode, and a liquid electrolyte circulates between the two in a narrow gap. When the direct current is applied, some material in the workpiece will dissolve into the electrolyte, and gradually form the shape in accordance with the shape of the tool. Because of this, one can machine conductive materials with a minimum of cutting forces and without the traditional tool-workpiece contact due to the essentially electrochemical nature of material removal [25].

Current density, applied voltage, electrolyte composition, electrolyte flow rate, inter-electrode spacing, and tool-feed rate are all factors that affect ECM performance. Common electrolytes are aqueous solutions of suitable salts selected based on the process type and the material of the workpiece. Manufacturing turbine blades, aerospace parts, complex cavities, medical implants and precision components using conductive alloys that are difficult to machine are typical applications of ECM. The main benefits are that it is extremely wear resistant, has minimal residual mechanical stress and can produce complex shapes with acceptable surface quality. ECM is however limited to materials that are electrically conductive, and the electrolyte flow, corrosion, stray machining and dimensional accuracy must all be controlled. Environmental management for electrolyte handling and disposal is also suitable.

❖ Ultrasonic Machining (USM)

Hard, brittle, and non-conductive materials are typically machined using ultrasonic machining, a mechanical non-conventional method. It operates by using ultrasonic frequencies to vibrate a shaped tool while feeding an abrasive slurry between the tool and the item. The tool's high frequency oscillation causes the material's surface to develop microfractures, which gradually remove the material. The method is especially beneficial with harder material and/or brittle material that is difficult to cut using traditional methods. USM is not the standard chip-forming cutting technique, so it can be used to cut complex parts and relatively low thermal and mechanical loading [26].

The performance of USM is influenced by a number of variables, including vibration frequency, vibration amplitude, applied static load, abrasive type, abrasive concentration, slurry flow, and tool shape. Silicon carbide, boron carbide, aluminium oxide, and diamond are common abrasives that are selected based on the workpiece's hardness and the specifications needed for the machining process. Glass, ceramics, quartz, sophisticated composites, and some hard materials in electronics, optics, biomedical devices, and precision engineering are just a few of the uses for USM. It has many benefits, such as being able to machine electrically non-conductive materials, relatively low thermal damage and for intricate holes and cavities. The process, however, may not be as efficient in terms of material removal compared to some other processes, and tool wear, abrasive use, and limited machining depth may impact productivity and cost.

3.3. Water Jet Machining and Plasma Arc Machining

Water Jet Machining (WJM) is a technique that may be applied to a wide variety of materials, such as metals, plastics, ceramics, and composites, by cutting parts with a high-strength stream of water that is frequently mixed

with abrasive materials to reduce the temperature effect on the workpiece. A high-temperature ionised gas stream is used in plasma arc machining (PAM) to melt and remove material, particularly from conductive metals [27]. In both processes, extensive use is made in the aerospace, automotive and industrial manufacturing fields. The major disadvantage of water jet machining is that it can be quite expensive to operate and can wear out the nozzle, and plasma arc machining can cause edge defects, heat affected zones and fumes.

❖ **Water Jet Machining (WJM)**

Water jet machining is a non-conventional machining operation which is performed by pressurized water stream, which is directed through a small nozzle to remove or cut the material. The water jet forces mechanical energy into a small stream to cut or separate material in accordance with a programmed cutting path. Pure water jet machining is particularly suitable for relatively soft materials like rubber, plastics, textiles, paper and some foodstuffs. In the case of harder materials, abrasive water jet machining (AWJM) can be used by adding abrasive particles, typically garnet, to the water flow, thereby enhancing the cutting efficiency [28]. This abrasive-assisted process is capable of cutting a variety of materials including metal, ceramics, stone, glass, and composite materials.

The performance of water jet machining is affected by water pressure, nozzle diameter, stand-off distance, traverse speed, abrasive type and feed rate, and the characteristics of workpiece. This process is relatively cool for most materials, which is ideal for those that can be affected by heat such as deformation, burning or metallurgical changes. It can be used for cutting aerospace composites, automotive panels, architectural stone, industrial plates and complex sheet materials. The benefits are minimal thermal damage, the flexibility of cutting paths, and handling of a variety of materials. It can be expensive, however, particularly for abrasive systems, and nozzle wear, water usage, disposal of abrasive, and the ability to cut very thick or complex features should be taken into consideration.

❖ **Plasma Arc Machining (PAM)**

Plasma arc machining is a thermal machining process, in which the material is melted and removed from a workpiece by a high-temperature, ionized gas stream. The plasma is formed by an electric arc, and is forced through a nozzle to create a high-energy, focused jet. The plasma heats the work-piece and melts a portion, and the high velocity gas stream blows away the molten material from the cutting area. Plasma arc machining is used mainly on electrically conductive materials, and is most suitable for cutting materials that have high melting temperatures or large thicknesses. It is frequently considered to be some form of thermal cutting, and is grouped with the non-conventional material removal processes due to the use of concentrated thermal energy instead of conventional mechanical cutting [29].

The performance of the PAM is influenced by arc current, arc voltage, the composition of plasma gas, its flow rate and nozzle design, stand-off distance and cutting speed. Typical plasma gases include air, nitrogen, argon, and various other appropriate gas mixtures for the material and application. Many different applications use PAM, such as shipbuilding, structural steel fabrication, automotive manufacturing, heavy engineering, and metal cutting in industry. The essential benefits are: high cutting speed, processing of relatively thick conductive materials and applicability to automatic cutting systems. If the parameters are not optimized, it can create a heat affected zone, dross, edge oxidation and dimensional deviations as by-products of the process. Other hazards, such as noise, fumes, intense light and high temperature, also demand effective ventilation, protective equipment, and proper safety controls.

4. COMPARATIVE ANALYSIS OF MACHINING PROCESSES

A comparative study of conventional and non-conventional machining processes is vital in understanding the performance, suitability, and limitations of the processes in advanced manufacturing applications. Traditional manufacturing techniques, such as turning, milling, drilling, and grinding, primarily use mechanical cutting or abrasive processes to remove material, while non-conventional manufacturing processes use electrical, thermal, chemical, electrochemical, or high-pressure fluid energy [30]. The selection of an appropriate process depends on the properties of the material, the geometry of the component, the production volume, dimensional accuracy, surface finish, and manufacturing cost. These processes can be systematically compared to help manufacturers identify appropriate processes to enhance productivity, product quality, and resource utilization.

4.1. Material Removal Rate and Surface Finish

Machining productivity is best measured by MRR, or the volume of material removed from a material per unit time. For typical engineering materials, traditional machining techniques such as turning, milling, or drilling have a reasonably high material removal rate when operated under ideal conditions [31]. Grinding normally runs at lower

rates of material removal for precision grinding but still offers good surface quality. The performance of the non-conventional processes varies with their functioning mechanism. The geometry, material qualities, or process parameters determine the choice of high-speed cutting methods, such as plasma arc machining or abrasive water jet machining. Other options include electrical discharge machining, electrochemical machining, ultrasonic workpieces, and laser beam machining.

Surface finish indicates the surface texture and irregularities of a surface of a machined part and directly affects seal ability, wear, friction, fatigue strength, and reliability of a component. Grinding can yield very close dimensional tolerances and very polished surface finishes, turning and milling can yield good surface finish if the proper tools and cutting parameters are used [32]. Electrochemical machining may give smooth surface finishes without conventional cutting marks or electrical discharge machining may leave craters and a recast layer due to localized melting and re-solidification, among non-conventional processes. Water jet machining usually minimises thermal effects, surface oxidation, or edge imperfections that might occur with plasma arc machining and laser beam machining. Therefore, the rate of material removal, surface quality, and overall part quality are all factors to be considered when choosing a machining process.

4.2. Accuracy, Tool Wear and Energy Consumption

Dimensional accuracy is the capability of a machining process to make parts that meet the required dimensional and geometric tolerances. Favourable selection of machine tools, cutting tools, fixtures, and process control can be used to achieve high accuracy using conventional machining. CNC turning is a technology that enhances repeatability as well as multi-axis milling, precision drilling and grinding can produce complex components [33]. Non-conventional machining processes provide other options for manufacturing complex cavities, narrow slots, micro-holes and complex profiles. Wire EDM is suitable for precise contours and laser beam machining can be used for fine cutting and micro-feature production. Complex shapes can be produced with minimal mechanical stress from electrochemical machining but with an impact of the stray dissolution on the dimensional control. The actual accuracy obtained will depend on the capability of the equipment, the process parameters, the properties of the workpieces and the required tolerance.

Another area of consideration of the machining performance is the consumption of energy and tool wear. Wear is caused by friction, temperature, mechanical loading and repeated contact between cutting tools and the work in conventional machining. Tools for turning and milling may need to be replaced or reconditioned and grinding wheels need to be dressed from time to time. In many cases, non-conventional processes either minimize or eliminate the wearing of conventional cutting tools and have other types of tools or consumable wear. In the processes, the electrodes or wire in EDM and USM are consumed during the process, the abrasives wear in USM, and optical or nozzle components need to be maintained for laser and plasma systems [34]. The energy consumption depends on the machining mechanism, the efficiency of the machines, material removal rate, cooling demands, and auxiliary systems. Therefore, energy efficiency is crucial for both parameter selection and for tool condition monitoring and process planning, in order to boost productivity and minimise environmental impact.

4.3. Cost and Operational Efficiency

Machining process cost comprises equipment investment, tooling cost, energy cost, labour cost, maintenance cost, consumables, handling of coolant or electrolyte, and post-processing cost. The conventional machining equipment is prevalent, and the traditional process of turning, milling, drilling and grinding is suitable for general components and large-scale production and is generally economical. But there may be more tool wear, longer machining times and finishing costs with hard materials or difficult geometries [35]. Non-conventional machining equipment may require greater capital cost and expertise in its use. Electrodes and dielectric fluid are needed with EDM, electrolyte circulation and treatment are required with ECM, the cost of the laser source and optical system is required with laser machining and water and abrasive material is required with abrasive water jet machining. The cost of these facilities should be compared with the quality and productivity that is provided by each technique.

Efficiency in operation: The capability of producing the desired output with the necessary quality and with minimum time, material waste, energy consumption and production cost. Conventional machining is well suited for standard parts, repetitive jobs, high-volume production, and when combined with CNC automation. It is beneficial to use non-conventional machining in situations where parts have complex shapes, difficult-to-machine materials, or low mechanical loading [36]. Hybrid machine systems could further enhance efficiency by employing both conventional and non-conventional processes as best suited for those individual processes. For instance, conventional milling can be used to remove the bulk of a part and then the intricate features and precision finishing can be done using EDM or grinding. Finally, the most economic and efficient machining process depends not just

on the process itself but on the overall manufacturing process, setup and machining time, finish, inspection process and waste management process.

Table 1: Summary of Literature Review on Sustainable and Advanced Machining Processes

Author Name Ref	Topic Covered	Research Study Title
Lv et al. [37] (2017)	Reduction of spindle acceleration energy consumption in machine tools	An Investigation into Reducing the Spindle Acceleration Energy Consumption of Machine Tools
Yusuf et al. [38] (2021)	Energy consumption and minimization strategies for machine tools in manufacturing	A Review of Energy Consumption and Minimisation Strategies of Machine Tools in Manufacturing Process
Muniraju et al. [39] (2024)	Sustainable machining techniques for nitinol shape memory alloys, including eco-friendly EDM	Exploring Sustainable Machining Processes for Nitinol Shape Memory Alloy: A Review of Eco-Friendly EDM and Other Techniques
Chatterjee et al. [40] (2017)	Selection of non-traditional machining processes using hybrid multi-criteria decision-making methods	A Novel Hybrid Method for Non-Traditional Machining Process Selection Using Factor Relationship and Multi-Attributive Border Approximation Method
Chavoshi and Luo [41] (2015)	Hybrid micromachining technologies and their role in improving precision and machining efficiency	Hybrid Micro-Machining Processes: A Review

5. APPLICATIONS IN ADVANCED MANUFACTURING

Advanced manufacturing is the application of contemporary manufacturing methods, such as modern machining techniques, automation, precision engineering and novel materials to create components of high quality and efficiency with greater reliability [42]. The production of most standard components is still carried out using conventional machining methods like turning, milling, drilling and grinding, while non-conventional methods such as EDM, LBM, ECM, USM and water jet machining are used to make complex shapes and precision components. The choice of suitable machining process depends on the material properties, dimensional tolerances, surface finishes, production requirements and the cost. They are becoming increasingly vital across various aerospace, automotive, biomedical, electronics and other industries where precision, performance and the reliability of product manufacturing are at a premium.

5.1. Aerospace and Automotive Industries

Aerospace and automotive applications call for machining processes that ensure high dimensional accuracy, structural reliability and excellent surface integrity. Turbine shafts, structural components, landing gear parts, and engine components can be manufactured through the use of conventional milling, turning and grinding processes, which are extensively used in the aerospace manufacturing industry [43]. The non-conventional processes, especially EDM and laser beam machining, are extremely advantageous when used to produce turbine blade cooling holes, complex cavities and precise features in difficult-to-machine alloys. Water jet machining is also used to cut composite structures and lightweight materials without causing thermal damage. The processes are used to manufacture lightweight, high-strength parts that are required to meet challenging mechanical and thermal requirements throughout use.

In the automotive sector, machining technologies are employed to produce engine blocks, crankshafts, transmission gears, brake parts, fuel injection parts, and precision fasteners. Turning, Milling, Drilling, Grinding are used to produce large quantities of parts that require consistent size and surface finish. CNC machining centres can further enhance the productivity due to the automatic operation, while laser machining can achieve precision cutting, precision trimming and precision drilling of selected components [44]. While EDM can be employed for creating dies, moulds and complex tooling, water jet machining can aid the processing of automotive composites and sheet materials. Advanced machining technologies, computer-aided manufacturing, and automation contribute to the production of lightweight, energy-efficient vehicles, as well as the consistency of the components produced.

5.2. Biomedical and Electronics Manufacturing

In biomedicals, components need to be manufactured with precision, biocompatible and reliable for use in medical applications, which necessitates the use of machining processes. Orthopedic implants, surgical instruments, dental parts, and prosthetic devices are made from conventional turning, milling and grinding processes. Nonsense machining methods offer more capabilities for manufacturing complex geometry and hard-to-machine materials [45]. The ability to form complex shapes with EDM and laser process is available for appropriate conductive materials, and ultrasonic machining can be used to shape brittle materials like ceramics. Electrochemical machining can yield complex surfaces, with minimum mechanical stress, in conductive alloys. These processes are especially crucial in the production of parts with precise dimensions and smooth surfaces, as well as for parts that have intricate shapes. A variety of material compatibility, surface integrity, cleanliness and post-processing requirements have to be taken into account to ensure that the manufactured biomedical components satisfy the relevant performance and safety requirements.

Machining processes are used in electronics manufacturing to create parts and components associated with semiconductors, electronic housings, precision connectors, circuit-board features, heat sinks and micro-scale structures. Laser beam machining has become an essential process for precision cutting, drilling, marking and micromachining, due to its great flexibility and its capability to produce small features. Machining of brittle materials like glass, quartz or ceramics found in electronic or optical devices is possible by ultrasonic machining [46]. Conventional milling/grinding processes are used to achieve accurate surfaces and components, whilst other more specialized non-conventional processes are used to assist the manufacture of more complex features that might be hard to produce using mechanical cutting. More compact electronic devices, high density packaging and precise components are becoming more important and are making advanced machining technologies that provide higher dimensional control, repeatability, and manufacturing flexibility more important.

5.3. Machining of Advanced and Difficult-to-Cut Materials

Many advanced and difficult-to-cut materials are employed in engineering due to their high strength, hardness, corrosion resistance, thermal stability, and lightweight properties. These comprise hardened steels, ceramics, carbon-fibre-reinforced polymers, Ni-based superalloys and titanium alloys. However, traditional machining processes can lead to high cutting forces, rapid tool wear, high temperature, vibration, and surface integrity defects when machining such materials [47]. High strength at high temperatures is a hallmark of nickel-based superalloys, in contrast to the poor thermal conductivity of titanium alloys, which can cause heat to concentrate in the cutting area. Since mechanical machining is not suitable for ceramics and glass, which are durable but brittle, they are quickly damaged. Opting for the right process and fine-tuning its parameters are thus critical for achieving satisfactory production and component quality.

Many of these difficult materials can be effectively processed by non-conventional machining processes. EDM can be used for cutting or drilling complex features of electrically conductive materials such as selected superalloys and hardened steels, and laser beam machining can be used to cut or drill complex features of a variety of metals and other materials that are compatible with the laser beam. For alloys that cannot be mechanically worked, electrochemical machining can apply it, and for brittle non-conductive material like ceramics and glass, ultrasonic machining can be used. Abrasive water jet machining is especially useful for cutting composites since it does not produce extensive heat affected zones as do thermal cutting methods [48]. Each process, however, has its own limits of material compatibility, surface quality, cost and productivity. Conventional, non-conventional and hybrid machining technologies are thus complementary and are capable of a flexible solution for the manufacturing of advanced materials, and can enhance precision, reduce defects and meet the strict demands of industry.

6. CONCLUSION

The review concludes that, conventional and non-conventional machining processes complement each other in advanced manufacturing. While traditional processes like turning, milling, drilling, and grinding are suitable for general production, high material removal rates, and precision finishing, non-conventional processes are more adaptable to complex shapes, hard materials, and delicate components. The choice of the process will be determined by material properties, dimensional accuracy, surface finish, production requirements, energy use, cost and others. Additionally, the seamless integration of hybrid machining capabilities, CNC automation, and artificial intelligence can further enhance productivity, accuracy, and operational efficiency. Sustainable machining, energy optimization, decreased tool wear and environmentally friendly manufacturing should be targeted in future developments to provide cost-effective, reliable and high-quality production.

REFERENCES

1. Gupta, K., & Laubscher, R. F. (2017). Sustainable machining of titanium alloys: A critical review. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 231(14), 2543–2560. https://doi.org/10.1177/0954405416634278
2. Zhao, G., Zhao, B., et al. (2024). Nontraditional energy-assisted mechanical machining of difficult-to-cut materials and components in aerospace community: a comparative analysis. *International Journal of Extreme Manufacturing*, 6(2), 022007. https://doi.org/10.1088/2631-7990/ad16d6
3. Roy, M. K., Ray, A., & Pradhan, B. B. (2017). Non-traditional machining process selection – an integrated approach. *International Journal for Quality Research*, 11(1), 71–94. https://doi.org/10.18421/IJQR11.01-05
4. Kim, D.-H., Kim, T. J. Y., et al. (2018). Smart machining process using machine learning: A review and perspective on machining industry. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 5(4), 555–568. https://doi.org/10.1007/s40684-018-0057-y
5. Brinksmeier, E., Meyer, D., Huesmann-Cordes, A. G., & Herrmann, C. (2015). Metalworking fluids—Mechanisms and performance. *CIRP Annals*, 64(2), 605–628. https://doi.org/10.1016/j.cirp.2015.05.003
6. Jawahir, I. S., Attia, H., Biermann, D., Duflou, J., Klocke, F., Meyer, D., Newman, S. T., Pušavec, F., Putz, M., Rech, J., Schulze, V., & Umbrello, D. (2016). Cryogenic manufacturing processes. *CIRP Annals*, 65(2), 713–736. https://doi.org/10.1016/j.cirp.2016.06.007
7. Deshpande, Y. V., Ayer, S., Agrawal, T., Agrawal, V., Madankar, T. A., & Barve, P. S. (2023). Application of smart strategies for sustainable manufacturing of conventional machining process: a review. *Journal of The Institution of Engineers (India): Series C*, *104*(6), 1267-1289.
8. Sen, B., Mia, M., Krolczyk, G. M., Mandal, U. K., & Mondal, S. P. (2021). Eco-friendly cutting fluids in minimum quantity lubrication assisted machining: A review on the perception of sustainable manufacturing. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 8, 249–280. https://doi.org/10.1007/s40684-019-00158-6
9. Zurita, O., Di-Graci, V., & Capace, M. (2018). Effect of cutting parameters on surface roughness in turning of annealed AISI-1020 steel. *Revista Facultad de Ingeniería*, 27(47). https://doi.org/10.19053/01211129.v27.n47.2018.7928
10. Yue, C., Gao, H., Liu, X., Liang, S. Y., & Wang, L. (2019). A review of chatter vibration research in milling. *Chinese Journal of Aeronautics*, 32(2), 215–242. https://doi.org/10.1016/j.cja.2018.11.007
11. Bai, Q., Wang, P., Cheng, K., Zhao, L., & Zhang, Y. (2024). Machining dynamics and chatters in micro-milling: A critical review on the state-of-the-art and future perspectives. *Chinese Journal of Aeronautics*, 37(7). https://doi.org/10.1016/j.cja.2024.02.022
12. Xu, J., Geier, N., Shen, J., Krishnaraj, V., & Samsudeensadham, S. (2023). A review on CFRP drilling: Fundamental mechanisms, damage issues, and approaches toward high-quality drilling. *Journal of Materials Research and Technology*, 24, 9677–9707. https://doi.org/10.1016/j.jmrt.2023.05.023
13. Yang, M., Kong, M., Li, C., et al. (2023). Temperature field model in surface grinding: A comparative assessment. *International Journal of Extreme Manufacturing*, 5(4), 042011. https://doi.org/10.1088/2631-7990/acf4d4
14. Ding, W., Li, M., Li, B., & Xu, J. (2021). Recent progress on surface integrity of grinding difficult-to-cut metal materials. *Journal of Aeronautical Materials*, 41(4), 36–56. https://doi.org/10.11868/j.issn.1005-5053.2021.000031
15. Mohanraj, T., Shankar, S., Rajasekar, R., Sakthivel, N. R., & Pramanik, A. (2020). Tool condition monitoring techniques in milling process—A review. *Journal of Materials Research and Technology*, 9(1), 1032–1042. https://doi.org/10.1016/j.jmrt.2019.10.031
16. Serin, G., Sener, B., Ozbayoglu, A. M., & Unver, H. O. (2020). Review of tool condition monitoring in machining and opportunities for deep learning. *International Journal of Advanced Manufacturing Technology*, 109, 953–974. https://doi.org/10.1007/s00170-020-05449-w
17. Pimenov, D. Y., Bustillo, A., Wojciechowski, S., Sharma, V. S., Gupta, M. K., & Kuntoğlu, M. (2023). Artificial intelligence systems for tool condition monitoring in machining: Analysis and critical review. *Journal of Intelligent Manufacturing*, 34(5), 2079–2121. https://doi.org/10.1007/s10845-022-01923-2
18. Pedroso, A. F. V., Sebbe, N. P. V., Silva, F. J. G., Campilho, R. D. S. G., Sales-Contini, R. C. M., Martinho, R. P., & Casais, R. B. (2024). An in-depth exploration of unconventional machining techniques for INCONEL® alloys. *Materials*, 17(5), 1197. https://doi.org/10.3390/ma17051197
19. Wang, X., Ding, W., & Zhao, B. (2022). A review on machining technology of aero-engine casings. *Journal of Advanced Manufacturing Science and Technology*, 2022011. https://doi.org/10.51393/j.jamst.2022011
20. Paul, L., Babu, J., & Paulo Davim, J. (2019). Non-conventional micro-machining processes. In *Materials Forming, Machining and Post Processing* (pp. 109-139). Cham: Springer International Publishing.
21. Sarala Rubi, C., Prakash, J. U., Juliyana, S. J., Čep, R., Salunkhe, S., Kouřil, K., & Gawade, S. R. (2024). Comprehensive review on wire electrical discharge machining: A non-traditional material removal process. *Frontiers in Mechanical Engineering*, 10, 1322605. https://doi.org/10.3389/fmech.2024.1322605
22. Slătineanu, L., Dodun, O., Coteaţă, M., Nagîţ, G., et al. (2020). Wire electrical discharge machining—A review. *Machines*, 8(4), 69. https://doi.org/10.3390/machines8040069
23. Abhilash, P. M., & Chakradhar, D. (2020). Surface integrity comparison of wire electric discharge machined Inconel 718 surfaces at different machining stabilities. *Procedia CIRP*, 87, 228–233. https://doi.org/10.1016/j.procir.2020.02.037
24. Jia, X., Chen, Y., Liu, L., Wang, C., & Duan, J. (2022). Advances in laser drilling of structural ceramics. *Nanomaterials*, 12(2), 230. https://doi.org/10.3390/nano12020230

25. Gopal, P. M., Kavimani, V., Gupta, K., & Marinkovic, D. (2023). Laser-based manufacturing of ceramics: A review. *Micromachines*, 14(8), 1564. https://doi.org/10.3390/mi14081564
26. Liu, L., Xu, Z., Hao, Y., & Teng, Y. (2025). Electrochemical cutting with flexible electrode of controlled online deformation. *International Journal of Extreme Manufacturing*, 7(1), 015104. https://doi.org/10.1088/2631-7990/ad8734
27. Zhou, H., Zhang, J., Yu, D., Feng, P., Wu, Z., & Cai, W. (2019). Advances in rotary ultrasonic machining system for hard and brittle materials. *Advances in Mechanical Engineering*, 11(12). https://doi.org/10.1177/1687814019895929
28. Llanto, J. M., Tolouei-Rad, M., Vafadar, A., & Aamir, M. (2021). Recent progress trend on abrasive waterjet cutting of metallic materials: A review. *Applied Sciences*, 11(8), 3344. https://doi.org/10.3390/app11083344
29. Cinar, Z., et al. (2018). Developments in plasma arc cutting (PAC) of steel alloys: A review. *Jurnal Kejuruteraan*, 30(1). https://doi.org/10.17576/jkukm-2018-30(1)-02
30. Singh, K., Kumar, R., Singh, S., Kumar, R., Sead, F. F., & Lozanović, J. (2025). Non-conventional machining of Monel-400 alloy: A critical review of techniques, challenges, and sustainable prospects. *Frontiers in Mechanical Engineering*, 11, 1639320. https://doi.org/10.3389/fmech.2025.1639320
31. Shastri, R. K., Mohanty, C. P., Dash, S., Gopal, K. M. P., Annamalai, A. R., & Jen, C.-P. (2022). Reviewing performance measures of the die-sinking electrical discharge machining process: Challenges and future scopes. *Nanomaterials*, 12(3), 384. https://doi.org/10.3390/nano12030384
32. Liao, Z., la Monaca, A., Murray, J., Speidel, A., Ushmaev, D., Clare, A., Axinte, D., & M'Saoubi, R. (2021). Surface integrity in metal machining—Part I: Fundamentals of surface characteristics and formation mechanisms. *International Journal of Machine Tools and Manufacture*, 162, 103687. https://doi.org/10.1016/j.ijmachtools.2020.103687
33. la Monaca, A., Murray, J. W., Liao, Z., Speidel, A., Robles-Linares, J. A., Axinte, D. A., Hardy, M. C., & Clare, A. T. (2021). Surface integrity in metal machining—Part II: Functional performance. *International Journal of Machine Tools and Manufacture*, 164, 103718. https://doi.org/10.1016/j.ijmachtools.2021.103718
34. Saxena, K. K., Qian, J., & Reynaerts, D. (2018). A review on process capabilities of electrochemical micromachining and its hybrid variants. *International Journal of Machine Tools and Manufacture*, 127, 28–56. https://doi.org/10.1016/j.ijmachtools.2018.01.004
35. Sapkota, G., Ghadai, R. K., Čep, R., Shanmugasundar, G., Chohan, J. S., & Kalita, K. (2024). Enhancing efficiency in photo chemical machining: A multivariate decision-making approach. *Frontiers in Mechanical Engineering*, 10, 1325018. https://doi.org/10.3389/fmech.2024.1325018
36. Lv, J., Tang, R., Jia, S., & Liu, Y. (2016). Experimental study on energy consumption of computer numerical control machine tools. *Journal of Cleaner Production*, 112, 3864–3874. https://doi.org/10.1016/j.jclepro.2015.07.040
37. Lv, J., Tang, R., Tang, W., Liu, Y., Zhang, Y., & Jia, S. (2017). An investigation into reducing the spindle acceleration energy consumption of machine tools. *Journal of Cleaner Production*, 143, 794–803. https://doi.org/10.1016/j.jclepro.2016.12.045
38. Yusuf, L. A., Popoola, K., & Musa, H. (2021). A review of energy consumption and minimisation strategies of machine tools in manufacturing process. *International Journal of Sustainable Engineering*, 14(6), 1826–1842. https://doi.org/10.1080/19397038.2021.1964633
39. Muniraju, M., et al. (2024). Exploring sustainable machining processes for nitinol shape memory alloy: A review of eco-friendly EDM and other techniques. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. https://doi.org/10.1007/s40430-023-04642-8
40. Chatterjee, P., Mondal, S., Boral, S., Banerjee, A., & Chakraborty, S. (2017). A novel hybrid method for non-traditional machining process selection using factor relationship and multi-attributive border approximation method. *Facta Universitatis, Series: Mechanical Engineering*, 15(3), 439–456. https://doi.org/10.22190/FUME170508024C
41. Chavoshi, S. Z., & Luo, X. (2015). Hybrid micro-machining processes: A review. *Precision Engineering*, 41, 1–23. https://doi.org/10.1016/j.precisioneng.2015.03.001
42. Sarikaya, M., Gupta, M. K., Tomaz, I., Pimenov, D. Y., Kuntoğlu, M., Khanna, N., & Yıldırım, Ç. V. (2021). A state-of-the-art review on tool wear and surface integrity characteristics in machining of superalloys. *CIRP Journal of Manufacturing Science and Technology*, 35, 624–658. https://doi.org/10.1016/j.cirpj.2021.08.005
43. García-Martínez, E., Miguel, V., et al. (2019). Sustainable lubrication methods for the machining of titanium alloys: An overview. *Materials*, 12(23), 3852. https://doi.org/10.3390/ma12233852
44. Ronoh, K., Mwema, F., Dabees, S., & Sobola, D. (2022). Advances in sustainable grinding of different types of the titanium biomaterials for medical applications: A review. *Biomedical Engineering Advances*, 4, 100047. https://doi.org/10.1016/j.bea.2022.100047
45. Hof, L. A., & Abou Ziki, J. (2017). Micro-hole drilling on glass substrates—A review. *Micromachines*, 8(2), 53. https://doi.org/10.3390/mi8020053
46. Zhang, Y., Zhang, K., Xu, Y., Tong, W., Wang, J., & Ming, W. (2026). A review of non-laser and laser machining for through-glass via fabrication. *Micromachines*, 17(7), 796. https://doi.org/10.3390/mi17070796
47. Kaya, E., et al. (2017). Effects of cutting parameters on machinability characteristics of Ni-based superalloys: A review. *Open Engineering*, 7. https://doi.org/10.1515/eng-2017-0037
48. Zhang, J., Zheng, Z., Huang, K., Lin, C., Huang, W., Chen, X., Xiao, J., & Xu, J. (2024). Field-assisted machining of difficult-to-machine materials. *International Journal of Extreme Manufacturing*. https://doi.org/10.1088/2631-7990/ad2c5e