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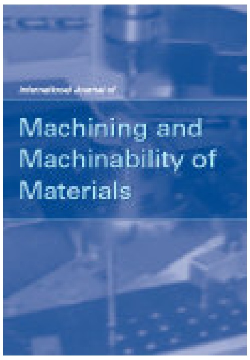

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Abstract: This paper presents a comprehensive overview of oxy-fuel, plasma, waterjet, and laser cutting, alongside drilling and milling operations, establishing the foundational knowledge required for conceptualising an integrated, multifunctional portal machine. Such a system aims to execute all five processes within a single unified architecture, addressing the demands of next-generation manufacturing systems that prioritise flexibility, modularity, and minimal process fragmentation. Fundamental principles, operational advantages, and integration barriers associated with each technology are highlighted, including mechanical, thermal, and infrastructural challenges. The study outlines the technological requirements for combining these processes within a shared machine platform, considering aspects such as tool interchangeability, energy supply, workspace configuration, and control system

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integration. Particular attention is given to the compatibility of process parameters, safety considerations, and the potential impact on machining accuracy and productivity.

Keywords: oxy-fuel cutting; plasma cutting; waterjet cutting; laser cutting; drilling and milling; metal sheets; hybrid machining centres.

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1 Introduction

Metal processing has undergone continuous technological evolution: over the past century, the emergence of new energy sources, control systems, and material requirements has driven the diversification of metalworking techniques, including mechanical machining, thermal cutting (such as oxy-fuel, plasma, and laser cutting), and additive and hybrid manufacturing.

At the same time, the development of advanced cutting technologies significantly expanded the range of materials and applications that could be processed efficiently. Thermal cutting methods such as oxy-fuel and plasma cutting made it possible to process thick structural steels and electrically conductive metals at high speeds, while laser cutting introduced unprecedented levels of precision and flexibility for complex geometries. In case of electro-thermal material removal [electrical discharge machining (EDM)] controlled electrical discharges between an electrode and a conductive workpiece is created in a dielectric fluid, enabling high-precision machining of hard and complex geometries without mechanical cutting forces (Sanchez et al., 2004). In parallel, non-thermal technologies such as abrasive waterjet cutting emerged as effective solutions for machining heat-sensitive materials and composites without inducing thermal distortion or microstructural changes.

Table 1 Overview of cutting and trimming techniques

Technique	*Type*	*Process principle*	*Applications and materials*
Punching	Mechanical	Tool presses through material to create holes or shapes	Sheet metals
Nibbling	Mechanical	Successive punching to follow contours	Thin sheet metals
Oxy-fuel cutting	Thermal	Combustion and oxidation	Carbon steel, Shipyards, construction, repairs
Plasma cutting	Thermal	Ionised gas jet melting	Conductive metals, HVAC, sheet metal, structural steel
Waterjet cutting	Abrasive/ mechanical	Erosion via high-pressure stream and abrasive	Aerospace, tooling, architecture composites, metals, ceramics
Laser cutting	Thermal	Focused beam melting/ vaporising	Automotive, electronics, prototyping, metals, polymers
Electrical discharge machining (EDM)	Electrical/ thermal	Material removal by electrical discharges between electrode and workpiece in a dielectric fluid	Electrically conductive materials; hard metals and alloys

Modern manufacturing research increasingly focuses on hybrid and multifunctional machine tools capable of combining several processing methods within a single system. Such approaches aim to reduce production time, optimise floor space usage, and enhance overall production flexibility. The integration of diverse manufacturing technologies therefore represents an important step toward more efficient, adaptive, and sustainable metal processing systems capable of meeting the growing demands of contemporary industrial production. Each of the applied methods has their advantages and limitations in terms of precision, energy efficiency, cost, and applicability to specific materials and thickness ranges (Kónya and Kovacs, 2024; Pawanr and Gupta, 2024).

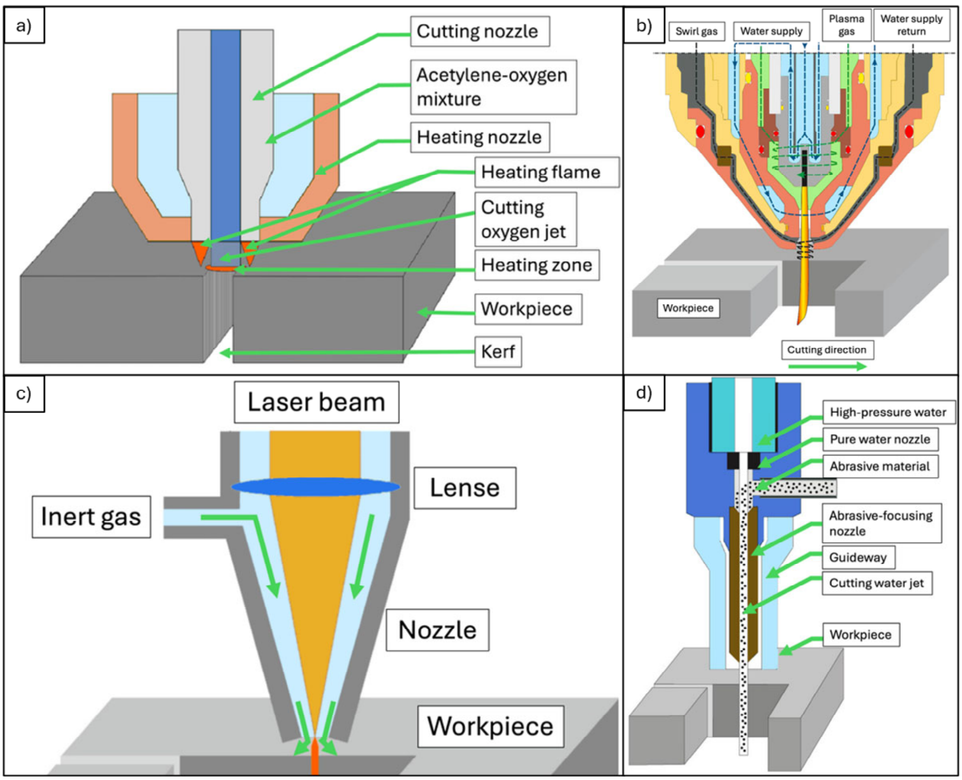
Oxy-fuel cutting, one of the oldest thermal cutting methods, has been widely used for heavy carbon steels due to its simplicity and robustness (Charles and Chater, 1978). The introduction of plasma cutting in the mid-20th century extended these capabilities to non-ferrous metals and offered higher cutting speeds and improved edge quality (Diekhoff et al., 2024). Later laser cutting brought a new level of precision and automation, enabling complex geometries and minimal heat-affected zones (Wang et al., 2024; Zhang et al., 2024). In parallel, computer numerical control (CNC) – controlled machining and robotic welding have evolved rapidly, forming the basis of modern smart factories (Makulavičius et al., 2023). More recently, additive manufacturing and hybrid technologies have introduced the possibility of combining material deposition and subtractive finishing within a single system (Stavropoulos et al., 2020). Water jet cutting, a cold, abrasive-based process that enables precise cutting of heat-sensitive and hard materials without generating a heat-affected zone, was first developed in the early 1930s for industrial applications and gained widespread use in the 1970s with the introduction of abrasive additives, enabling precise cutting of metals, composites, and other hard materials (Wang et al., 2023). However, its wet, mechanical nature and abrasive residues make it difficult to integrate with thermal methods such as laser, plasma, or oxy-fuel cutting, which rely on localised heating. Additionally, differences in cutting speed, machine rigidity, and surface preparation requirements pose challenges for multi-method processing in hybrid manufacturing systems (Zhang et al., 2021).

Despite advancements, current industrial practice often relies on separate, specialised machines for each process, and results on multi-purpose systems are limited, because large-scale portal machine architectures exhibit structural compliance, thermal deformation, and dynamic instabilities, thus advanced compensation and control strategies are required (Gomez-Acedo et al., 2013). Droß et al. presented a robot based manufacturing cell in which metal parts are mechanically pre treated, additively completed (thermoplastic application) and subsequently finished by machining, within one modular system, demonstrating the concept of combining additive, subtractive and forming techniques in one cell. Large freeform geometries were enabled by multiple robot stations, a multi-axis part transfer system using digital twins and a five-axis CNC machine tool in the study of Jared et al. (2024) who integrated multi-material wire-arc additive manufacturing, fringe projection scanning metrology, robotic part handling and finish machining. Avram et al. (2022) presented a hybrid five axis gantry/portal style machine combining additive and subtractive capabilities, including dual laser sources and integrated vision/monitoring systems. Stavropoulos et al. (2020) studied the optimal process window for additive manufacturing considering its integration with conventional technologies including part inspection, quantifying geometrical and dimensional part deviations, and demonstrated a laser deposition and milling system. Hybrid metal subtractive-additive manufacturing concepts were presented by Scott et al. and Pereira et al. too (Pereira et al., 2021; Smith et al., 2024).

Fragmentation increases production time, space requirements, and operational complexity. In response to these challenges, the present work focuses on highlighting the limits and advantages of a multi-purpose portal equipment capable of integrating multiple metal processing methods within a platform. Such a system would enable flexible, high-efficiency manufacturing by allowing the rapid reconfiguration of processing modes according to the requirements of the workpiece.

The aim of this study is therefore to design and evaluate the conceptual framework, technical feasibility, and potential industrial impact of an integrated, multi-functional portal system integrating oxy-fuel, plasma, water-jet and laser cutting, as well as mechanical drilling and milling. By merging traditional and modern metal processing technologies into a single, modular structure, this research seeks to contribute to the next generation of flexible manufacturing systems aligned with the principles of Industry 4.0.

Figure 1 Schematic representation of thermal cutting methods, (a) oxy-fuel (b) plasma (c) laser (d) abrasive waterjet (see online version for colours)



2 Overview of the integrated manufacturing technologies

Building upon the historical evolution and hybridisation of metal processing technologies discussed in the introduction, the following sections provide a detailed technical review of five core cutting and machining methods that are candidates for integration into a multi-purpose portal system. These include oxy-fuel, plasma, waterjet, and laser cutting (Figure 1), as well as drilling and milling operations. Each subsection systematically explores the operating principles, technological maturity, process control requirements, material compatibility, and automation readiness of the respective methods. This analysis supports the evaluation of their interoperability and potential for modular integration within a unified, flexible manufacturing platform aligned with Industry 4.0 paradigms.

2.1 Overview of the oxy-fuel cutting technology

Oxy-fuel cutting [Figure 1(a)], with other words flame cutting, is one of the oldest and most robust thermal cutting technologies, which is used primarily for low-alloy and carbon steels. The fundamental principle involves the chemical oxidation of steel in a high-temperature environment, facilitated by a mixture of fuel gas and pure oxygen. This technique has seen extensive industrial application for over a century due to its operational simplicity, cost-effectiveness, and adaptability in field conditions. In the oxy-fuel cutting process, a preheating flame is directed onto the metal surface until it reaches its ignition temperature, typically around 900–950°C for carbon steel. At this point, a separate stream of highly pure oxygen (usually 99.5% or higher) is released, which reacts exothermically with the iron in the steel to form iron oxide (Fe_3O_4), generating additional heat. This heat sustains the reaction and allows the oxidation front to propagate through the thickness of the metal, effectively severing it. The resulting molten iron oxide slag has a lower melting point than the base metal and is expelled from the kerf by the force of the oxygen jet (Adedayo, 2011; Charles and Chater, 1978). The process is limited to ferrous metals that can oxidise readily. It is ineffective for cutting non-ferrous alloys like aluminium, copper, or stainless steels, which form refractory oxides or do not oxidise in a controllable way. Oxy-fuel cutting also generates a wide heat-affected zone (HAZ), potentially altering the microstructure of adjacent material, and often necessitates post-processing such as grinding or slag removal to meet surface finish specifications.

A significant advantage of oxy-fuel cutting lies in its independence from electrical power, making it suitable for remote or outdoor operations, such as shipyards, construction sites, and heavy equipment repair in the field. Moreover, oxy-fuel cutting equipment ranges from handheld torches to CNC-guided cutting tables, offering scalability for both manual and automated applications. Operational parameters such as oxygen pressure, fuel type, nozzle design, cutting speed, and plate thickness must be precisely controlled to achieve optimal results. Higher oxygen pressures increase cutting speed but may result in wider kerfs and more slag. The flame composition oxidising, neutral, or carburising also affects the quality of the cut; an oxidising flame is generally used to promote efficient metal oxidation (Ramakrishna et al., 2018).

Modern developments in oxy-fuel cutting include hybrid systems that integrate oxy-fuel and plasma cutting heads on a single machine, allowing operators to switch methods based on material thickness. Additionally, integration with CAD/CAM software and CNC control has enabled greater precision and repeatability, even for complex geometries. Predictive maintenance using IoT-enabled sensors can monitor gas flow rates and nozzle wear in real-time, reducing downtime and improving cut consistency. While newer technologies such as laser and plasma cutting offer better precision and higher speeds on thin or non-ferrous materials, oxy-fuel cutting retains its place in heavy industry due to its capability to cut thick steel economically and its robustness in harsh environments (Jo et al., 2024; Zero et al., 2024).

Despite its maturity and low operating cost, oxy-fuel cutting faces increasing competition from plasma and laser technologies due to its relatively poor dimensional accuracy, large heat-affected zone, and limited applicability to ferrous materials. Further research is required to better understand oxidation kinetics and heat transfer phenomena in thick-section cutting, particularly for automated process optimisation. Oxy-fuel cutting remains economically attractive for processing of heavy steel; however, its low suitability for high-precision manufacturing limits its role in future advanced production.

2.2 Plasma cutting process description

Plasma cutting [Figure 1(b)] is a high-velocity, high-temperature thermal cutting method widely used for processing electrically conductive metals. The technique operates by generating an electric arc between a non-consumable electrode (usually tungsten) and the workpiece. This arc ionises a compressed gas (such as air, nitrogen, oxygen, or argon-hydrogen), forming a plasma jet that reaches temperatures exceeding 25,000°C. The kinetic energy and thermal intensity of the plasma jet are sufficient to melt the material, while the gas flow expels the molten metal from the kerf. There are three principal variants of plasma cutting: conventional air plasma, precision (high-definition) plasma, and hybrid plasma systems. Conventional systems use single gas (often air) and are typically suited for low-precision cutting. In contrast, precision plasma systems utilise specialised nozzles, multiple gas streams, and tighter control of arc formation, achieving edge quality and tolerance levels near those of laser cutting particularly on steel up to 25 mm thick. Hybrid systems combine features of arc and plasma processes or plasma with other cutting heads to expand flexibility (Stevens, 2000).

Factors such as current level, gas composition, flow rate, nozzle diameter, and stand-off distance influence kerf geometry, surface roughness, dross formation, and thermal distortion (Salonitis and Vatousianos, 2012). Excessive arc voltage can widen the kerf and reduce precision, while too low a current leads to incomplete cutting and slag adherence. Optimal cutting speed is essential; too slow allows heat build-up and HAZ expansion, whereas too fast leads to incomplete severance and edge bevelling. Recent research in plasma cutting has focused on improving cut edge quality, minimising consumable wear, and enhancing arc stability via advanced current waveforms and machine learning-based control (Milovančević et al., 2024).

The plasma cutting process offers distinct advantages over oxy-fuel cutting, particularly in its ability to cut non-ferrous materials such as stainless steel, aluminium, copper, and exotic alloys. It also produces a narrower kerf, reduced HAZ, and smoother edges. Because of its high cutting speeds and CNC compatibility, plasma cutting is a mainstay in sheet metal fabrication, heating, ventilation and air conditioning (HVAC) duct manufacturing, and structural steel processing (Sawdatkar et al., 2024).

Modern plasma cutting systems are integrated with CAD/CAM software and real-time feedback systems, allowing adaptive control of arc length and gas flow. These technologies contribute to consistent cut quality and minimal rework. Advanced plasma cutting systems can achieve significantly improved hole quality, producing geometries with reduced taper and enhanced dimensional accuracy, which in many applications can approach the requirements of bolt-ready holes and reduce the need for secondary drilling operations in structural steel (Górka, 2023). Hybrid additive-subtractive systems that combine plasma cutting with welding or surface hardening are also under development for integrated manufacturing solutions.

Safety considerations in plasma cutting include managing intense UV and infrared radiation, toxic fumes (notably hexavalent chromium from stainless steel), and high noise levels. Enclosures, local exhaust ventilation, and personal protective equipment (PPE) are mandatory for occupational safety. Environmental advances include water-table cutting beds and fume extraction units that minimise airborne particulates.

Plasma cutting offers a favourable balance between productivity, versatility, and investment cost. However, challenges remain in improving arc stability, reducing wear, and minimising dross formation. Its ability to process a wide range of conductive metals makes it an important technology in modern manufacturing and a suitable candidate for integrated systems.

2.3 Laser cutting process characteristics

Laser cutting [Figure 1(c)] is a high-precision, non-contact thermal cutting process that utilises a focused beam of coherent light to melt, burn, or vaporise material along a defined path (Steen and Mazumder, 2010; Berczeli et al., 2024). The laser beam generated by CO_2, Nd:YAG, or fibre lasers is directed through a system of mirrors and lenses to achieve a spot size as small as 0.1 mm, concentrating several kilowatts of power onto the workpiece. An assist gas (oxygen, nitrogen, or air) is simultaneously delivered coaxially with the beam to expel molten material. Fibre lasers, based on solid-state technology, dominate industrial applications due to their high electrical efficiency (~30–40%), superior beam quality ($M^2 < 1.5$), and minimal maintenance requirements (Chang and Wei, 2020). They are especially effective on reflective metals like aluminium, brass, and copper, which previously posed challenges to CO_2 laser systems. CO_2 lasers still retain niche use for non-metallic materials such as wood, plastics, and fabrics due to their longer wavelength (10.6 µm) (Kechagias et al., 2025).

The laser cutting process is governed by several interdependent parameters: laser power, focal position, cutting speed, gas type and pressure, and material thickness (Alsaadawy et al., 2024). Precise control of these variables determines the kerf width, surface roughness, dross formation, and heat-affected zone. For example, nitrogen-assisted cutting yields oxidation-free edges suited for stainless steel in the food and medical industries (Zubko et al., 2020), while oxygen improves cutting efficiency on mild steel but induces edge oxidation (Ivarson et al., 1996). One of the key advantages of laser cutting is its ability to produce intricate geometries and tight tolerances (±0.05 mm or better) without tool wear (Kaplan, 2000). Ali et al. showed that although waterjet cutting shows less out of roundness in cutting hole diameter and less reduction in strength, difference between upper and lower diameter is larger in comparison with the laser hole making (Ali et al., 2014). Additionally, the process supports high-speed cutting (up to 30 m/min for thin sheets), high repeatability, and minimal setup time, that makes it ideal for prototyping and just-in-time (JIT) production systems in automotive, electronics, and aerospace sectors (Wetzig et al., 2019). Modern laser systems are fully integrated with CAD/CAM software and often employ real-time feedback mechanisms such as capacitive height sensors and vision-based alignment. These systems ensure consistent beam focus and adapt to material flatness variations (Bach et al., 2024; Belšak et al., 2024). Some platforms also support mixed-material nesting and automatic nozzle change to further enhance flexibility (Li et al., 2023). Limitations of laser cutting include diminished performance on very thick sections (>25 mm), potential for micro-cracking in heat-sensitive alloys, and high initial capital costs. Nonetheless, the reduction in post-processing, minimal waste, and adaptability to automation continue to drive adoption across high-value manufacturing.

Emerging developments in laser cutting include ultrashort pulse lasers (femtosecond/picosecond), which enable cold ablation with negligible thermal damage particularly valuable for micromachining and biomedical components (Tünnermann et al., 2023). Beam shaping technologies such as adjustable ring-mode lasers allow dynamic tuning of energy distribution for optimised edge quality in thick or composite materials (Bischoff et al., 2019).

Laser cutting provides excellent precision and automation potential but requires high capital investment and precise process control. Ongoing research focuses on beam-material interactions and the processing of reflective or thick materials. Its industrial significance continues to grow due to increasing demands for flexible and digitally controlled manufacturing.

2.4 Waterjet cutting methodology

Waterjet cutting is a non-thermal material removal process that uses a high-velocity stream of water, often mixed with abrasive particles, to perform precision cutting on a wide range of materials. As a cold-cutting technique, it is especially valued for applications where thermal deformation, material hardening, or oxidation must be avoided. The process operates by pressurising water to levels between 3,000 and 6,000 bar using intensifier pumps, then forcing it through a small diameter orifice (Hashish, 1984).

Abrasive waterjet cutting [Figure 1(d)], the most widely used variant for metals, introduces abrasive particles (commonly garnet) into the water stream via a mixing chamber. These particles, accelerated by the water, erode the workpiece surface via micro-mechanical impact (Hofy et al., 2025). This allows effective cutting of hard materials such as steel, titanium, ceramics, and composites with edge tolerances comparable to conventional machining. Key process parameters affecting cut quality include water pressure, nozzle diameter, stand-off distance, abrasive type and flow rate, and cutting speed (Hashish, 1991). Higher pressures and optimised abrasive flow yield smoother surfaces and narrower kerfs but may reduce component life and increase operational costs. The stand-off distance typically 1–3 mm must be tightly controlled to ensure coherent jet impact and avoid divergence (Hashish, 2024).

Waterjet cutting is CNC-compatible and is extensively used in industries such as aerospace, automotive, tooling, and architecture. In aerospace, for example, it enables the precision machining of titanium alloys and fibre-reinforced polymers (FRPs) without inducing delamination or heat damage. In the study of Akkurt (2014) eight cutting methods were compared in case of AISI 304 stainless steel cutting surfaces, and abrasive waterjet cutting was proven to be the best thanks to the lack of HAZ and deformation. In contrast, oxygen cutting changed the most significantly the hardness of the material, and both laser and plasma treatment resulted in wider HAZ than waterjet cutting. In automotive prototyping and architectural panelling, the method allows for complex shapes and engravings without secondary finishing (Hashish, 2024). One notable drawback is the taper effect, where the top and bottom kerf widths differ due to jet divergence and energy loss with depth. Advanced systems use tilting heads or dynamic jet compensation algorithms to mitigate this (Du et al., 2024). Also, thick-section cutting (over 150 mm) becomes time-consuming and energy-intensive, making other methods more efficient for such cases.

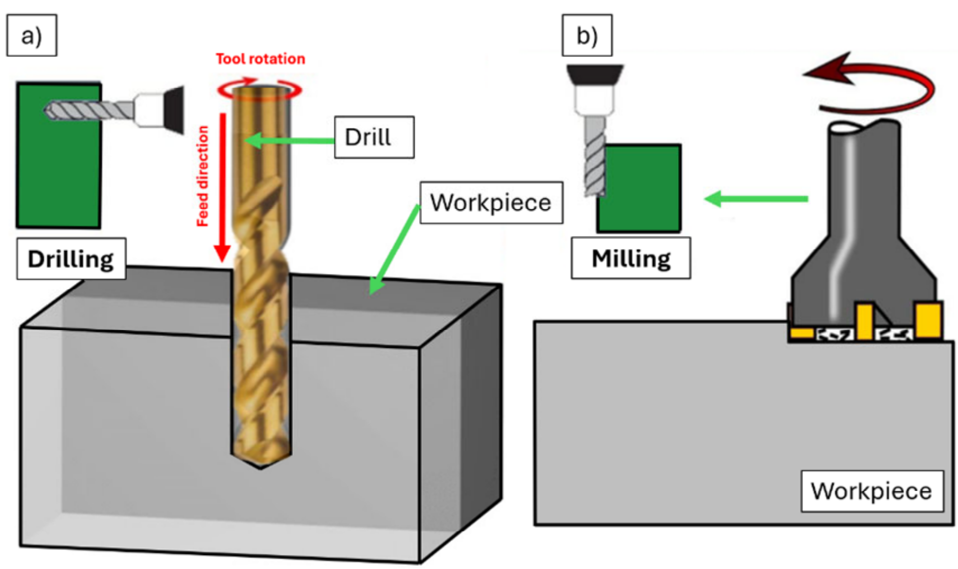
Waterjet cutting produces no hazardous fumes or dust, and used garnet can often be recycled. Closed-loop water systems minimise water usage and environmental impact. However, abrasive disposal and pump energy consumption remain challenges in high-volume operations. Recent innovations include the use of pulsed waterjets and hybrid processes where waterjet is combined with laser or ultrasonic vibration to enhance material removal efficiency. Research into adaptive control systems using AI for real-time parameter tuning is ongoing to further improve cut quality and reduce waste (Popan et al., 2024).

Waterjet cutting is distinguished by its ability to process virtually any material without thermal damage. Nevertheless, abrasive consumption, nozzle wear, and relatively low cutting speeds are important limitations. This technology plays a critical role in aerospace and composite manufacturing, although its integration with thermal processes presents considerable engineering challenges.

2.5 Drilling and milling operations

Drilling and milling (Figure 2) are subtractive machining processes fundamental to modern manufacturing. They operate by removing material using rotating cutting tools under controlled feed and speed conditions. Although these processes predate digital manufacturing, their integration into CNC systems has transformed them into highly automated and precise operations for producing complex geometries and fine tolerances.

Figure 2 Schematic representation of mechanical methods, (a) drilling (b) milling (see online version for colours)



Drilling is a uniaxial process that uses a multi-point tool typically a twist drill to produce cylindrical holes in solid materials. The tool rotates at high speed while being advanced along its axis into the workpiece. Common applications include through-holes, blind holes, and pre-tapped holes for fasteners. Critical parameters include spindle speed (RPM), feed rate, and drill point geometry influence chip formation, tool life, and hole quality (Hassan et al., 2021; Shrinivas Balraj and Anitha, 2016). Cutting fluids or coolants are frequently employed in drilling to reduce tool wear, dissipate heat, and aid chip evacuation (Kočiško et al., 2023). In deep-hole drilling operations, specialised techniques such as gun drilling or peck drilling are applied to manage axial forces and avoid tool deflection. Surface finish and roundness tolerances are typically in the range of IT10–IT12 without reaming or honing (Li et al., 2013).

Milling is a multipurpose machining method in which a rotary tool with multiple cutting edges removes material while the workpiece is fed perpendicular to the tool's axis. Operations include face milling, slotting, contouring, and 3D surface machining. Vertical and horizontal milling machines enable different part geometries and orientations. CNC milling machines especially those with 4- or 5-axis capability can produce intricate components like turbine blades, molds, and biomedical implants. Toolpath strategies such as climb milling (preferred for CNC) and conventional milling influence chip load and surface finish (Li et al., 2013). In high-speed milling (HSM), shallow cuts at high spindle speeds enhance material removal rates while minimising thermal effects (Matuszak et al., 2023). A major breakthrough in milling process optimisation was achieved by Altintaş and Budak (1995), who introduced analytical stability lobe prediction methods for chatter-free machining. This work enabled the direct determination of stable spindle speed and depth-of-cut combinations, increasing productivity while maintaining machining accuracy; based on that stability lobe diagrams have since become standard tools in high-performance milling process planning.

Material selection affects machinability. Aluminium alloys are easily machined with high surface quality, whereas titanium and hardened steels require low feed rates and carbide tooling to avoid chatter and excessive heat. Tool coatings (e.g., TiAlN, DLC) further enhance wear resistance and enable dry machining in environmentally sensitive applications (Ali et al., 2025). Integrated machining centres often combine drilling, milling, tapping, and boring in a single setup with automatic tool changers (ATCs), reducing cycle time and setup errors. In Industry 4.0 environments, digital twins and real-time analytics support predictive maintenance, process optimisation, and closed-loop quality control (Fantozzi et al., 2025).

Recent advances include hybrid machining platforms that incorporate additive manufacturing heads, laser-assisted milling for hard materials, and AI-driven toolpath optimisation (Budak and Altintas, 1998; Cevik et al., 2025) Multi-sensor and model-based feedback strategies support adaptive machining by accounting for tool-workpiece coupled dynamics and stability lobe diagram (SLD) limits, thereby improving chatter avoidance and process robustness in thin-walled milling operations (Campa et al., 2006; Urbikain et al., 2012).

Drilling and milling are indispensable for achieving high dimensional accuracy and complex geometries. Research now focuses on tool wear, chatter suppression, and adaptive process control. In multifunctional portal systems, these operations impose the highest requirements on machine rigidity and positioning accuracy, making their integration particularly demanding.

2.6 Evaluation and comparison of integrated manufacturing technologies

In this section, five major metal processing methods with relevance to the design and integration of multifunctional manufacturing platforms are summarised in Table 2:

oxy-fuel cutting, plasma cutting, waterjet cutting, laser cutting, and drilling/milling. Each technique offers distinct process mechanics, material applicability, and control requirements that influence its role in an integrated system. Oxy-fuel cutting is robust and energy-independent, thus it is ideal for thick-section ferrous metals in field conditions. Plasma cutting offers broader material compatibility and speed, especially for non-ferrous metals, while waterjet cutting provides a cold process suitable for thermally sensitive and layered materials. Laser cutting contributes high precision and minimal heat-affected zones, supporting fine-feature fabrication and automation. Drilling and milling remain indispensable for subtractive finishing, creating holes, and complex geometry generation. Understanding the technical, operational, and integration characteristics of these processes is essential for evaluating their combined deployment in a modular, reconfigurable platform. The following comparative table highlights their key attributes to support system-level design decisions.

Table 2 Comparative summary on cutting and machining technologies

Technology	*Mechanism*	*Strengths*	*Limitations*	*Typical machine limits*
Oxy-fuel cutting	Oxidation via flame + O_2	Low cost, no electricity, thick-section cutting	Not for non-ferrous metals, large HAZ	Thickness up to 300–1,000 mm; tolerance ±1–3 mm; relatively slow cutting speed
Plasma cutting	Ionised gas (plasma arc)	High speed, non-ferrous capability, CNC adaptable	Dross, noise, fume, limited edge precision	Thickness 0.5–150 mm; tolerance ±0.2–1.5 mm; kerf width 1–5 mm
Waterjet cutting	High-pressure water + abrasive	No HAZ, versatile, fine tolerance	Taper, slow on thick materials, abrasive disposal	Thickness up to 200–300 mm; tolerance ±0.05–0.25 mm; slower at large thicknesses
Laser cutting	Focused light beam	Precision, tight tolerances, low waste	Expensive, thick-section limits, reflective metals	Thickness <25 mm (steel), <15 mm (Al); tolerance ±0.02–0.1 mm; kerf width 0.1–0.5 mm
Drilling/ milling	Rotating mechanical tools	Geometry control, CNC flexible, hybrid capable	Tool wear, heat, chatter in hard-to-machine materials	Hole diameters from <0.1 mm to >100 mm; tolerance ±0.01–0.1 mm; limited by tool reach and rigidity

2.7 Barriers and perspectives of integrated technologies

Although each presented manufacturing process offers distinct advantages – oxy-fuel for thick-section ferrous cutting, plasma for speed and versatility, waterjet for cold, high-precision cuts, laser for fine-feature thermal processing, and drilling/milling for geometric accuracy (Table 2) – the integration of these methods into a single multifunctional platform presents significant technical and systems-level challenges. The propagation of geometric and assembly errors in multitasking machine tools can be effectively modelled using homogeneous transformation matrices, where individual geometric deviations accumulate through the kinematic chain and influence the volumetric accuracy of the entire system (Díaz-Tena et al., 2013).

Table 3 Comparison of the industrial impacts and the rationale behind integrability

Technology	*Industrial impact*	*Integration advantages*	*Integration limitations*
Oxy-fuel cutting	Important for heavy steel fabrication (e.g., shipbuilding, construction). Low-cost and robust, but declining role in precision manufacturing.	Simple system architecture, low energy demand, well-suited for large portal frames; can be combined with other cutting heads (e.g., plasma) in hybrid systems.	Limited to ferrous materials; large heat-affected zone (HAZ); strong thermal load conflicts with laser and water-based systems; low suitability for high-precision integration.
Plasma cutting	Widely used in metal fabrication (steel structures, HVAC, general manufacturing). Good balance between cost, speed, and flexibility.	CNC-compatible, high cutting speed, works on all conductive metals; relatively easy integration with oxy-fuel and laser systems in hybrid setups.	Requires gas supply and fume extraction; dross formation, noise, and electromagnetic/thermal interference; difficult to combine with water-based processes.
Waterjet cutting	Key technology in aerospace and composite manufacturing; enables cold cutting without thermal damage.	Material-independent (almost all materials), no heat-affected zone; compatible with precision post-processing workflows; suitable for multi-material systems.	Incompatible with thermal processes due to water and abrasive media; slow on thick materials; high maintenance and waste handling requirements; requires isolated work zone.
Laser cutting	High-precision core technology in automotive, electronics, and advanced manufacturing. Highly automated and digitally integrated.	Excellent precision, high speed, minimal tool wear; fully CNC-integrated; suitable for complex geometries and hybrid manufacturing systems.	High capital cost; limited performance on very thick materials; sensitive optical systems (dust, water, contamination); strict safety and enclosure requirements.
Drilling/ milling	Fundamental subtractive processes in modern manufacturing; essential for holes, finishing, and high-accuracy geometry.	High dimensional accuracy; CNC automation; strong compatibility with digital manufacturing; supports multi-operation machining centres.	Requires high structural rigidity; sensitive to vibration and thermal deformation; significant dynamic loads; difficult integration with lightweight thermal cutting portal systems.

A central barrier arises from fundamental incompatibilities between process types (Table 3). Thermal processes such as laser and plasma cutting demand dry, clean environments, whereas waterjet operations introduce high-pressure water and abrasive residues. Without effective isolation through modular enclosures, robotic tool exchange, or dedicated subzones, cross-contamination could degrade optical components, corrode delicate thermal heads, and compromise operational reliability. Similarly, the differing infrastructure and environmental requirements – gas delivery systems for oxy-fuel and plasma, coolant management for machining, and precise motion control for laser – require complex coordination to maintain safe and effective operation. Laser cutting is a highly efficient and precise process, but it must be conducted under strict safety guidelines to protect both operators and the workspace. Radiation-protecting housing is normally required to contain the laser beam and prevent exposure to harmful radiation, ensuring that no stray beams escape during operation.

Mechanical machining processes, including drilling and milling, pose additional barriers despite spatial compatibility with thermal heads. Structural stiffness, chip management, and thermal deformation are critical concerns. For example, prior exposure to high thermal loads from oxy-fuel or plasma cutting can warp the workpiece, undermining subsequent milling accuracy unless active compensation or in-process metrology is implemented. Drilling operations generate high axial loads that may exceed the capabilities of gantry systems optimised for lightweight thermal heads, necessitating reinforced drive mechanisms or adjustable support structures. Beyond the present study, punching and nibbling, would present similar integration challenges due to the high localised impact forces during shearing operations. While punching is highly productive in the typical thickness of 0.5–12 mm (steel) and tolerance of ±0.05–0.2 mm regime, nibbling offers greater flexibility through successive overlapping punches, where the minimum corner radius is limited by the punch size (typically 0.5–6 mm; tolerance ±0.1–0.5 mm). Both processes require significantly higher structural rigidity and vibration resistance than thermal cutting heads.

Process synchronisation across such heterogeneous technologies represents another key challenge. Variations in cutting speed, heat input, kerf width, and surface preparation demand an intelligent control system capable of context-aware sequencing, thermal load balancing, and dynamic toolpath adaptation. Here, digital twins, multi-sensor feedback loops, and AI-driven optimisation emerge as essential enablers for ensuring process compatibility and real-time conflict resolution.

Beyond these technological considerations, the integration of multiple manufacturing processes also introduces challenges related to system architecture, maintenance, and operational workflow. A multifunctional platform must accommodate diverse tooling systems, power supplies, and auxiliary equipment within a shared structural framework while maintaining accessibility for servicing and calibration. Tool changing mechanisms must be robust and reliable, capable of handling different cutting heads, machining tools, and sensors without compromising positional accuracy. Additionally, maintenance strategies must account for the varying wear characteristics of consumables such as plasma nozzles, laser optics, abrasive waterjet components, and mechanical cutting tools.

Another important aspect concerns the management of process by-products and environmental conditions within the shared workspace. Thermal cutting generates fumes, molten slag, and high temperatures, while waterjet cutting produces water mist and abrasive waste. Effective extraction, filtration, and waste handling systems must therefore be integrated into the machine architecture to ensure both operational stability and occupational safety. These requirements further complicate the design of a compact and efficient multifunctional system.

Despite these integration barriers, the strategic potential of a hybrid, multi-modal system is substantial. Consolidating multiple processes on a single platform can reduce floor space, lower capital expenditures relative to maintaining separate machines, and enable seamless process chaining without intermediate repositioning. More importantly, it allows manufacturers to adapt operations dynamically to varying workpiece geometries, materials, or customer requirements, paving the way toward truly adaptive manufacturing.

From an integration perspective, the most compatible core technologies for a multifunctional manufacturing platform are plasma cutting, laser cutting, and drilling/milling operations. These processes generally operate in dry, CNC-controlled environments, which makes them easier to combine within a unified machine architecture. They also share similar requirements in terms of motion control, automation, and digital process management, allowing smoother integration in a common portal-based system. In contrast, abrasive waterjet cutting is the most challenging technology to integrate. High-pressure water and abrasive particles introduce a fundamentally different working environment, requiring isolated process zones and specialised waste and fluid management systems. Among all the considered methods, drilling and milling impose the highest structural demands on the machine system. These operations generate significant cutting forces and dynamic loads, requiring a highly rigid machine frame, strong drive systems, and excellent vibration damping to maintain accuracy and stability during operation. Finally, oxy-fuel cutting introduces the strongest thermal conflict. Its high heat input and wide heat-affected zone are incompatible with precision-focused technologies and also problematic when combined with water-based processes.

In the long term, the development of such integrated systems could significantly contribute to the realisation of flexible manufacturing environments capable of responding rapidly to changing market demands. By combining multiple processing technologies within a single, modular architecture, manufacturers may achieve greater efficiency, reduced production lead times, and improved product customisation capabilities, ultimately supporting the broader transition toward smart and resilient industrial production systems.

Currently there is no available technology that utilises all the methods presented in one piece of equipment, however, CNC milling with laser/plasma options are widely used in smaller working areas. In larger scale combinations of oxy-fuel and plasma cutting, as well as drilling are rather common and laser and plasma cutting with drilling for large workpieces in portal arrangement is also a matured solution, as well as plasma and oxyfuel cutting with drilling and milling. Adding other methods is to waterjet cutting is a challenge, however, waterjet with plasma option is available, while laser cutting with punching or different laser types are also present on the market.

3 Conceptual design requirement and future trends

The successful integration of oxy-fuel, plasma, laser, waterjet cutting, and drilling/milling operations into a single portal manufacturing system requires a carefully designed machine architecture to accommodate significantly different process requirements. The machine structure has to provide sufficient rigidity and vibration damping to support mechanically demanding drilling and milling operations while maintaining the positioning accuracy required for laser and plasma cutting. At the same time, thermal deformation caused by high-energy cutting processes needs to be minimised through the structural design and compensation strategies.

A modular tool-changing system is essential for enabling rapid transitions between different processing technologies enabling automatic exchange of thermal cutting heads, waterjet nozzles, and machining spindles while preserving positional accuracy and minimising setup times. Furthermore, the workspace should be organised into dedicated process zones to reduce cross-contamination between thermal and water-based operations and to facilitate efficient management of fumes, slag, water, and abrasive residues. The control architecture must integrate CNC motion control with process-specific subsystems, sensor networks, and safety functions. From a safety perspective, appropriate laser protection systems have to be applied, as well as gas supply monitoring, fume extraction units, and water management. Consequently, the conceptual design of a multifunctional portal machine requires a balanced combination of structural robustness, modularity, process isolation, and intelligent control to enable efficient and reliable multi-process manufacturing.

As it described above, smart machining concepts based on integrated sensing, adaptive control, and real-time process monitoring are key promotors for next-generation multifunctional manufacturing systems (Cheng et al., 2017). Cheng and Huo identified smart micro-tooling, integrated micromachining systems, and advanced process modelling as key future directions for enhancing the accuracy, productivity, and adaptability of micro-cutting technologies (Cheng and Huo, 2013). Zheng et al. (2018) proposed a conceptual framework for Industry 4.0 smart manufacturing systems, identifying cyber-physical systems (CPS), the industrial internet of things (IIoT), cloud computing, big data analytics, and artificial intelligence as the key technological drivers of future manufacturing. The authors highlighted smart design, machining, monitoring, control, and scheduling as the principal functional segments of intelligent production systems, emphasising the increasing importance of real-time data integration, autonomous decision-making, and interconnected manufacturing resources. The study identified enhanced flexibility, mass customisation, predictive maintenance, and self-optimising production as major future R&D directions for next-generation manufacturing environments. Digital twin technologies are expected to play a key role in this transition by ensuring continuous monitoring, error prediction, process optimisation, and closed-loop adaptive control (Fu et al., 2025). As a result, future machining systems will rely on multi-source data fusion, AI-driven decision-making, and high-fidelity digital twins to support real-time quality control and machining error compensation, thus self-optimising production systems will be the backbone of research for Industry 4.0 and emerging Industry 5.0 paradigms.

4 Conclusions

This paper presented a comprehensive overview of five major metal processing technologies – oxy-fuel cutting, plasma cutting, laser cutting, abrasive waterjet cutting, and conventional drilling and milling – focusing on their operating principles, technological capabilities, and their potential integration within a unified manufacturing platform. Based on the analysis, the following conclusions can be drawn:

1 The investigated manufacturing technologies provide complementary capabilities that cover a broad range of industrial requirements. Oxy-fuel cutting is advantageous for thick carbon steel sections, plasma cutting offers high productivity in case of

conductive metals, waterjet cutting is a good choice for heat-sensitive materials, laser cutting demonstrates superior precision, while drilling and milling ensure accurate hole making and geometric finishing.

2 Although the integration of these technologies into a portal platform is technically feasible, it requires careful system-level design. Successful implementation depends on the compatibility of machine architecture, tool exchange mechanisms, energy supply systems, workspace organisation, and process control strategies.

3 Barriers in integration arise from the different operating conditions of the techniques. Thermal cutting requires dry and controlled environments, while waterjet cutting introduces water. Drilling and milling impose mechanical stiffness and accuracy requirements that differ considerably from those of thermal cutting systems.

4 Advanced digital technologies are essential in effective process integration. Digital twins, real-time sensor networks, adaptive control systems, and artificial intelligence-based optimisation support process optimisation, toolpath planning, predictive maintenance, and quality assurance.

5 Multi-process portal machines have industrial potential despite technological challenges. Such systems reduce production lead times, minimise workpiece handling and repositioning, improve floor-space utilisation, and increase manufacturing flexibility, thereby supporting the transition toward Industry 4.0 and future smart manufacturing systems.

It can be concluded that among the five manufacturing technologies each process contributes unique capabilities that can complement one another within an integrated production environment. While substantial engineering challenges remain in combining thermal, mechanical, and water-based processes into a single platform, current technological developments suggest that, although commercially not available yet, such integration is technically feasible. The realisation of a multifunctional portal machine would represent a significant step toward more efficient, flexible, and sustainable manufacturing systems, providing a promising direction for future industrial innovation and research.

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Declarations

All authors declare that they have no conflicts of interest.

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