

THEORETICAL RESEARCH ON CUTTING METHODS USED IN THE AUTOMOTIVE INDUSTRY

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ABSTRACT: The present paper presents modern methods of cutting metallic materials used in the automotive industry, highlighting essential theoretical principles, process efficiency, cut quality, and economic implications. Among the methods discussed are laser cutting, water jet cutting, and electrical discharge machining (EDM), each having specific characteristics that determine their applicability in various industrial fields.
A review of the specialized literature shows that laser cutting and water jet cutting offer significantly higher cutting speeds and superior precision compared to traditional methods, making them preferred solutions in high-demand production environments. In contrast, mechanical cutting, although slower, proves to be a viable option for workshops with limited budgets or for the production of unique or small series parts.
The paper analyzes cutting methods in terms of operational costs, cutting precision, cutting speed, and equipment costs, highlighting that selecting the optimal cutting method is a matter of cost, efficiency, and the long-term vision of the management of the user company.
KEYWORDS: cutting, laser, electrical discharge machining, water jet, mechanical cutting

1. INTRODUCTION

In an ever-evolving industrialized world, manufacturing process efficiency has become a key priority for companies that aim to stay competitive in the market. The cutting process for metallic materials represents one of the most important stages in the production of parts and components used across various industries, from automotive to aerospace and mechanical engineering [1]. Over the past decades, technological advancements have led to the development of increasingly sophisticated cutting methods, which not only optimize performance but also reduce environmental impact and production costs [2].

Traditional cutting technologies, such as milling and turning, have been significantly improved, while modern methods, such as laser cutting, water jet cutting, and electrical discharge machining (EDM), have revolutionized material processing [3]. These techniques not only provide high precision but also greater flexibility regarding the shapes and sizes of the parts produced. For example, laser cutting enables the creation of complex contours without requiring special tools, reducing setup time and associated costs [1].

Another important aspect is the impact these processes have on the quality of the final products. Cuts made by modern methods, such as water jet cutting, do not affect the structure of materials, preserving their mechanical properties intact [2].

Recent statistics indicate that investments in modern cutting technologies have increased significantly, and companies adopting them are seeing a reduction in production costs and improvements in operational efficiency [3]. For instance, it is estimated that using laser cutting, by increasing cutting speed, can reduce manufacturing time by up to 30% without compromising the quality of the parts produced [1].

This paper aims to analyze various modern metal cutting methods, highlighting the operating principles, advantages, and disadvantages of each technique, as well as relevant industry statistics. Additionally, the authors provide a comparison of these processes in terms of efficiency, quality, and cost, offering concrete examples of these innovative technologies.

2.PRINCIPLES OF CUTTING METHODS

2.1 Mechanical cutting

Mechanical cutting is a material processing method that involves the use of cutting tools to remove material from a raw piece, resulting in the desired shape. This type of cutting is widely used in the manufacturing industry and is based on the principles of mechanics, employing specific tools to make precise, controlled cuts in various types of metals and alloys.

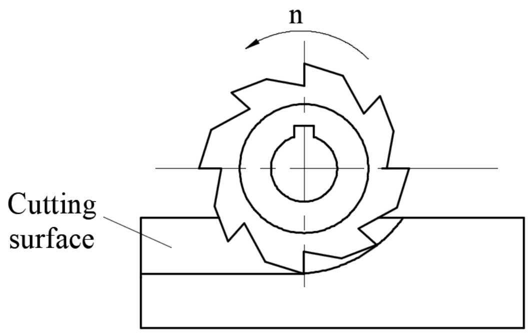

Figure 1. Mecanichal cutting

2.1.1. Operating principle

Mechanical cutting relies on the interaction between cutting tools and raw material. The process can be described in several steps:

- Material removal: Cutting tools, such as milling cutters, lathes, and punches, remove material by applying mechanical force. This is achieved through relative movements between the tool and the workpiece [4].
- Heat generation: The friction between the tool and the material generates heat, which can influence the material properties and lead to tool wear.
- Cutting control: Cutting speed, tool feed rate, and depth of cut are critical parameters that must be controlled to ensure cut quality and to prevent damage to the tool or workpiece [5].

2.1.2. Types of mechanical cutting

There are several types of mechanical cutting, each with its specific applications and advantages:

- Milling: Used to remove material from flat surfaces or create complex shapes. Milling cutters come in various shapes and sizes, and the process can be performed on vertical or horizontal milling machines [6].
- Turning: A cutting process used to shape cylindrical or conical forms. The material is fixed on a chuck, and cutting tools move to remove material from the exterior or interior surfaces [4].
- Punching: Involves using a die to cut or shape material into a specific form. It is commonly used in the production of metal parts for automobiles and industrial equipment [5].

2.1.3. Advantages

Mechanical cutting offers numerous advantages, including:

- Precision and control: Enables precise cuts and tight tolerances, essential in high-quality component manufacturing.
- Versatility: Can be used for a wide range of materials, including steels, aluminum, and alloys, thus meeting diverse industry needs.
- Relatively low costs: Although mechanical cutting equipment can be expensive, operating costs are often lower compared to advanced technologies like laser cutting [5].

2.1.4. Disadvantages

Despite its advantages, mechanical cutting also has some disadvantages:

- Tool wear: Cutting tools wear down over time, requiring frequent replacement, which can increase production costs.
- Limitations in processing hard materials: Mechanical cutting can be less effective for very hard materials, which may lead to rapid tool wear and lower cut quality [7].
- Waste generation: The cutting process can generate a significant amount of waste, especially in complex cuts where the initial material shape is not optimized for use [6].

2.2 Laser cutting

Laser cutting is an advanced processing technology that uses a focused laser beam to remove material from a workpiece. This method proves to be extremely precise and efficient, widely used in the industry for cutting metals and alloys. The technology has evolved significantly over the past decades, with applications in various fields, from automotive to aerospace.

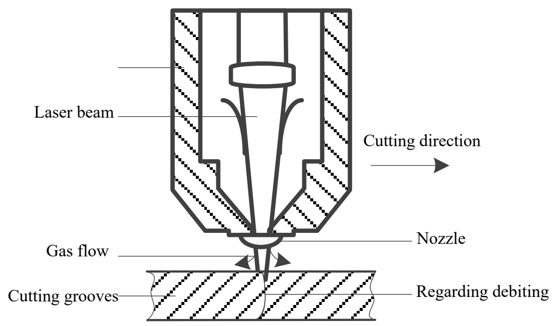

Figure 2. Laser cutting

2.2.1 Operating principle

Laser cutting is based on generating a laser light beam, which is focused through a lens to produce high power density on a small area of the cutting material. The process involves several steps:

- Laser beam generation: A laser, typically CO_2 or fiber, generates an intense light beam. This beam is amplified and directed through an optical system [8].
- Focusing: The laser beam is focused on the material's surface, generating extremely high temperatures. This heat causes the material to melt or vaporize [9].
- Material removal: The melted material is removed by a stream of gas, often nitrogen or compressed air, which blows the resulting material out of the cutting area [10].

2.2.2 Advantages

Laser cutting offers numerous advantages over traditional cutting methods, such as:

- High precision: Laser technology enables extremely precise cuts with tolerances of only a few tens of microns, essential for manufacturing complex components;
- Flexibility: It can cut a wide variety of shapes and sizes without requiring tool changes or molds, making it ideal for custom production;
- Waste reduction: Due to its high precision, laser cutting generates less material waste compared to traditional methods;
- Easy automation: Laser cutting machines can be easily integrated into automated production lines, contributing to increased efficiency and reduced production time [10].

2.2.3 Disadvantages

Although laser cutting has numerous advantages, there are also some disadvantages:

- High initial costs: Laser cutting equipment can be expensive, and the initial investment may be a barrier for smaller companies;
- Limitations in cutting thick materials: Although the technology is excellent for cutting thin metals, it may face difficulties in processing thicker materials, where cutting efficiency decreases [12];
- Sensitivity to reflectivity: Materials with reflective properties, such as copper and aluminum, can cause issues in the cutting process, affecting quality and efficiency [11].

2.3 Water jet cutting

Water jet cutting is a modern cutting method that uses a high-pressure water jet, with or without the addition of an abrasive substance, to remove material from a workpiece. This technology is extremely versatile and can be used to cut a wide range of materials, including metals, composites, glass, and even food products. The use of water jets has evolved from basic industrial applications to advanced cutting techniques, valued for its precision and efficiency.

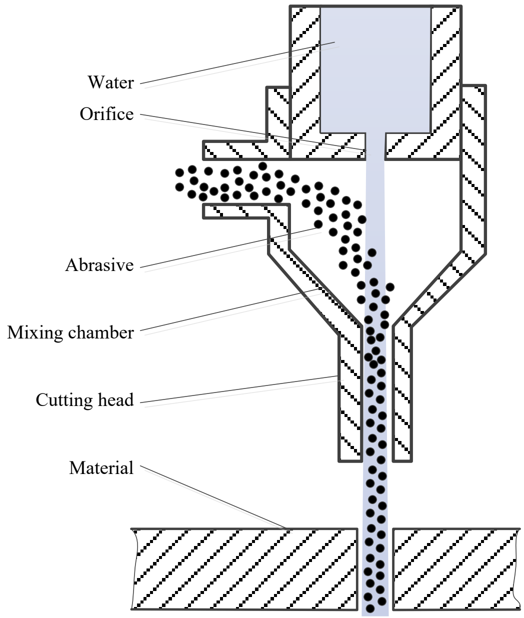

Figure 3. Water jet cutting

2.3.1 Operating principle

Water jet cutting involves generating an ultra-fine water jet accelerated to extremely high speeds, typically between 300 and 900 m/s. The process includes several essential steps:

- Jet generation: Water is pumped through a high-pressure pump system, reaching a pressure of approximately 4000-6000 bar. This water is then forced through a very small nozzle, where it transforms into a thin, powerful jet [13].
- Abrasive addition: For cutting hard materials, an abrasive material, such as garnet, can be added to the water jet. This combination enables effective cutting of materials like stainless steel or hard alloys [14].
- Interaction with the material: The water jet is directed at the material's surface, causing erosion and removal through a process of impact and abrasion. This method is particularly effective at creating clean cuts without causing heat-affected zones [12].

2.3.2 Advantages

Water jet cutting offers numerous advantages over traditional cutting methods:

- Versatility: It can cut a wide range of materials, including metals, plastics, glass, and composites, making it suitable for various industrial applications;
- Clean cuts: The water jet cutting process produces very clean, precise cuts, minimizing or eliminating the need for additional processing;
- No heat-affected zones: Since it does not involve high temperatures, no heat-affected zones

are created, which is crucial for maintaining material integrity;

- Eco-friendly: The process does not produce harmful waste or chemical by-products, making it an environmentally friendly alternative to traditional methods [13].

2.3.3 Disadvantages

Although water jet cutting has many advantages, there are also some disadvantages:

- Operational costs: Water jet cutting equipment can have high initial costs and significant maintenance requirements;
- Limitations with thick materials: Cutting very thick materials may be less efficient and may require longer processing times [12];
- Energy requirements: The technology depends on an efficient pump system, which may limit its use in certain environments or applications [14].

2.4 Electrical discharge machining (EDM)

Electrical Discharge Machining (EDM) is an advanced material processing technique that uses controlled electrical discharges to remove material from a workpiece. This method is extremely useful for cutting and shaping hard materials, such as alloy steels, hard metals, and materials difficult to process with traditional methods. EDM is widely used in the metalworking industries, especially for manufacturing molds, cutting tools, and components with complex shapes.

2.4.1 Operating principle

Electrical Discharge Machining is based on the principle of electrical erosion, which unfolds through the following steps:

- Generating electrical discharges: An electrode (typically made of copper or graphite) is brought near the workpiece, creating a dielectric gap between them. When the electric voltage between the electrode and workpiece exceeds a certain threshold, an electrical discharge (arc) is generated, vaporizing a small amount of material from the workpiece surface [15].

- Material erosion: Repeated electrical discharges cause controlled erosion of the material. Each discharge creates a small crater on the workpiece surface. This erosion continues until the desired shape is achieved [16].

- Cooling: A dielectric fluid (usually oil or water) is used to cool the workpiece and electrode, helping to remove particles of eroded material. This maintains process efficiency and prevents equipment damage [17].

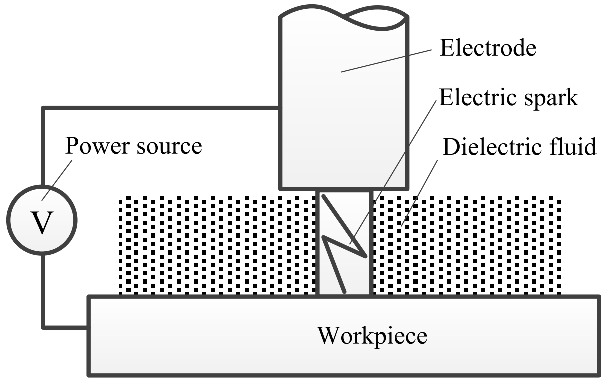

Figure 4. Electrical discharge machining (EDM)

2.4.2 Advantages

Electrical Discharge Machining offers numerous advantages that make it a popular choice in manufacturing industries:

- High precision: EDM provides a high level of accuracy, capable of producing complex shapes and fine details that would be difficult to achieve through other machining methods;
- Ability to process hard materials: The technique is ideal for cutting materials with high hardness, such as tool steels and special alloys;
- No thermal deformation: Since there is no physical contact between the electrode and the workpiece, EDM minimizes thermal deformation, preserving the material's structural integrity [17].

2.4.3 Disadvantages

However, Electrical Discharge Machining also has some limitations:

- High costs: EDM equipment can be expensive, and operating and maintaining it requires specialized personnel;
- Slow processing speed: Compared to traditional cutting methods, EDM has a slower processing speed, which can impact overall production costs;
- Limitations in processing thin materials: The technique is not effective for processing very thin materials, as it may cause damage [17].

3.COMPARATIVE ANALYSIS OF THE ADVANTAGES AND DISAVANTAGES OF CUTTING METHODS USED IN THE AUTOMOTIVE INDUSTRY

Material cutting is an essential stage in industrial processes, directly impacting the quality of finished products and the efficiency of the production process. Each cutting method—whether mechanical cutting, laser cutting, water jet cutting, or Electrical Discharge Machining (EDM)—has its own advantages and disadvantages. This section will provide a detailed analysis of the positive and negative aspects of the main cutting methods.

Tabel 1. Advantages and Disadvantages of Cutting Processes Used in the Automotive Industry

Process	Advantages	Disadvantages
Mechanical cutting	Lower costs; Simple equipment	Lower precision; Limitations in cutting hard materials
Laser cutting	Precise cuts; High speed	High costs; May affect surrounding material
Water jet cutting	Does not affect material structure; Versatile	High operational costs; Requires specialized equipment
EDM cutting	High precision; Ideal for hard metals	Long processing time; High costs

The graphs presented in Figure 5 show the performance characteristics of four cutting technologies (mechanical, laser, water jet, and electrical discharge machining - EDM) based on five criteria: cost, precision, materials cut, speed, and equipment complexity. Each axis of the graph represents a criterion, with higher values indicating better performance in that aspect. Interpretation by category of the performance values presented in figure 5:

1. Cost:
   - Mechanical cutting has a relatively low cost (score of 7) and is one of the most affordable methods.
   - Laser cutting and EDM have moderate costs (score of 6).
   - Water jet cutting is the most expensive (score of 5) due to the complexity of the equipment and necessary consumables.
2. Precision:
   - EDM and laser cutting offer the highest precision (scores of 10 and 9), making them ideal for fine detail work.
   - Water jet cutting has good precision (score of 8), but not at the level of laser or EDM.
   - Mechanical cutting offers the lowest precision (score of 5).
3. Materials cut**:**
   - Water jet cutting is the most versatile (score of 10), capable of cutting nearly any material, including metals, stone, and glass.
   - Mechanical and laser cutting are relatively versatile (scores of 7 and 6).
   - EDM can only cut conductive materials (score of 5).
4. Speed:
   - Mechanical and laser cutting are the fastest methods (scores of 8 and 9).
   - Water jet cutting and EDM are slower, particularly for thick materials or in the case of EDM, due to the slow erosion process.
5. Equipment complexity:
   - Mechanical cutting is the simplest technically (score of 4).
   - Laser, water jet, and EDM require more complex equipment, with EDM being the most complex (score of 8).

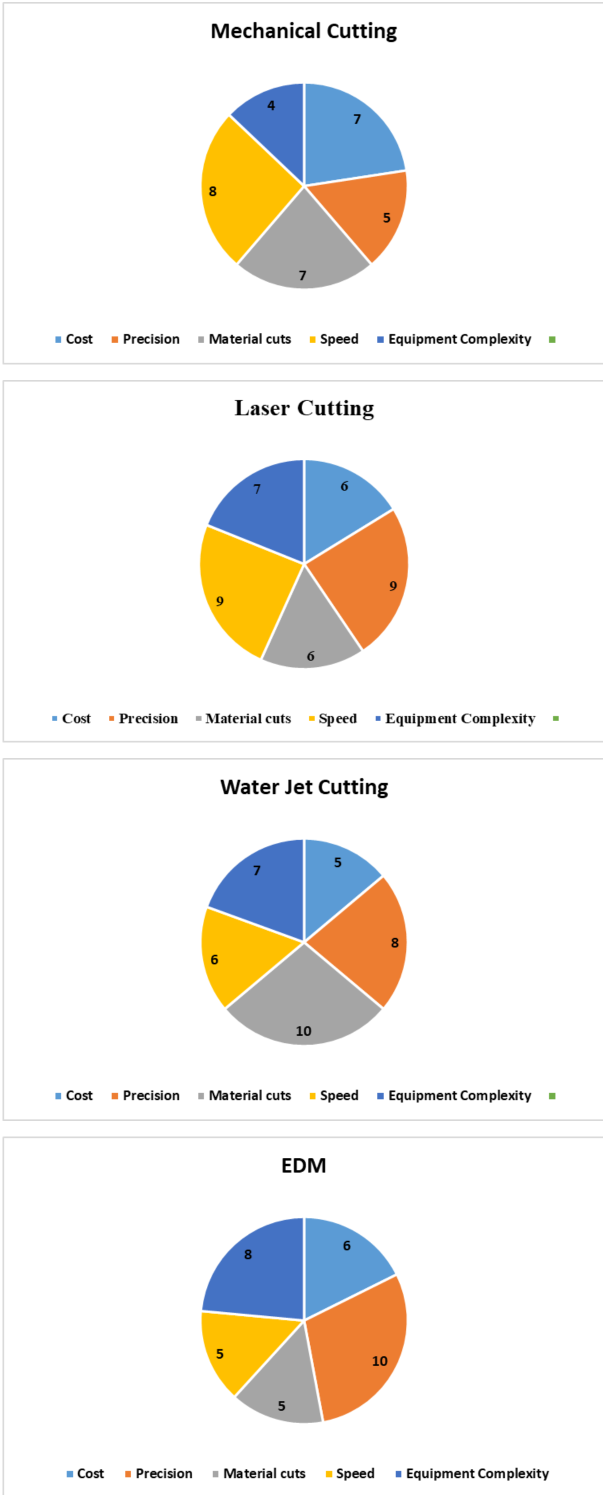

Figure 6. Graphical representation of performance cutting process

4.COMPARATIVE ANALYSIS OF CUTTING METHODS

A comparative analysis of cutting methods is essential for selecting the optimal technique based on the specific requirements of each project. Each cutting method has its own characteristics, advantages, and disadvantages, which influence the decisions of engineers and managers in the manufacturing industry. This section analyzes cutting methods based on three main criteria: efficiency, quality, and cost.

4.1. Efficiency

Efficiency refers to the speed and productivity of the cutting process. Laser cutting and water jet cutting are among the fastest methods available, allowing materials to be cut at significantly higher speeds than traditional methods. These techniques are particularly useful in industrial applications where high production volumes and critical delivery times are priorities. However, the high costs associated with equipment and maintenance may limit their use in mass production for certain types of materials or smaller projects.

In contrast, mechanical cutting, though slower, provides a more accessible solution for companies that do not require extreme cutting speeds. This method may be a preferred choice for the production of unique or small-batch parts where the initial cost of advanced equipment cannot be justified. Therefore, the choice of cutting method largely depends on the specific requirements of each project, including production volume, available time, and the type of material used [3].

4.2. Quality

Cutting quality is another essential aspect in comparing cutting methods. Laser cutting and electro-discharge machining (EDM) are regarded as superior options for achieving precise cuts and clean edges. These methods allow for highly controlled cutting processes, which reduce the risk of material deformation and ensure exact dimensions [15].

On the other hand, water jet cutting provides good quality but may require additional finishing, particularly when working with thicker materials or complex shapes. This is due to the fact that, while water jets can effectively cut most metals, adjustments to cutting parameters may be needed to achieve the desired results in certain cases [1].

Engineers must consider both the quality requirements of the final product and the specific material characteristics when choosing a cutting method.

4.3. Costs

Costs are a decisive factor in selecting a cutting method. Mechanical cutting has the lowest initial costs, making it more accessible for companies with limited budgets for advanced equipment. This makes it a preferred option for small workshops or projects with budget constraints [16].

In contrast, modern methods such as laser and water jet cutting provide a better long-term cost-benefit ratio, especially in industrial applications. While these methods have higher initial costs, their superior efficiency and precision can result in significant savings over time by reducing production times and waste generation [1]. Thus, investing in modern equipment can be justified by increased productivity and product quality.

4.4. Relevant Statistics

Statistics play an essential role in assessing the impact and popularity of various cutting methods. According to recent estimates, the global laser cutting market is valued at $3.5 billion in 2023, with an annual growth rate of 8%, reflecting the increasing demand for precise and efficient cutting solutions [2].

Water jet cutting accounts for approximately 15% of all cutting processes used in the industry. Its use is expanding due to its advantages in cutting materials of varying thicknesses and its ability to make clean cuts without altering the material structure [3].

In the global metalworking industry, EDM accounts for about 10% of total cutting processes, particularly in sectors such as mold manufacturing, medical devices, and precision electronic components. A 2023 report estimates the global EDM technology market at approximately $2 billion, with a compound annual growth rate (CAGR) of 6%, driven by the increasing demand for highly precise cuts in aerospace and automotive sectors [4].

Studies indicate that EDM usage has contributed to a 70% improvement in high-precision production processes, with 60% of companies in the hard material processing sector reporting reduced maintenance downtime due to this technology's high performance and precision [5].

A recent study found that 80% of metal processing companies consider implementing modern cutting technologies to have significantly improved their operational efficiency. Additionally, 65% of these companies reported a reduction in waste generated during the production process, underscoring the positive impact of these technologies on sustainability and profitability [1].

5.CONCLUSIONS

Each cutting method, whether mechanical cutting, laser cutting, water jet cutting, or electro-discharge machining (EDM) has unique applications and limitations. Selecting the appropriate method depends on various factors, including the type of material, associated costs, quality, and efficiency requirements, as well as the desired production volume. Based on these criteria, engineers and project managers must carefully assess the available options to determine the most suitable method for their specific needs.

For example, laser cutting offers high precision and is ideal for complex cuts, though it may be limited by high equipment costs and the types of materials it can process. In contrast, mechanical cutting, while slower and providing lower cut quality compared to advanced methods, remains an affordable option for mass production of simpler parts. This diversity in methods reflects the varied needs of the industry and underscores the importance of adapting technologies to market demands.

As technologies continue to advance, it is essential for engineers and industry specialists to stay up to date with the latest innovations in cutting processes. Technological advances, such as the integration of artificial intelligence and automation in production, can significantly enhance the efficiency and quality of cutting operations. Moreover, recent research in materials and cutting technologies opens new opportunities for developing more efficient and environmentally friendly solutions.

In conclusion, the selection process for cutting methods is not solely a matter of cost or efficiency but also of long-term vision. Just as markets and technologies evolve, so must companies striving to remain competitive. Investments in modern technologies and continuous staff training are crucial to maximize the potential of each cutting method and to address emerging challenges in the industry.

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