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Impacto ambiental de los procesos industriales de mecanizado por arranque de viruta con tornos paralelos mediante métodos innovadores: revisión del estado del arte

Environmental impact of industrial machining processes by chip removal with parallel lathes through innovative methods: a state-of-the-art review

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Palabras claves: mecanizado, arranque, viruta, tornos, paralelos, sostenibilidad, refrigeración, criogénica, pulverización.

Resumen

Introducción: El mecanizado de metales por arranque de viruta es la técnica fundamental en la industria manufacturera, siendo el torneado el proceso de mecanizado tradicional más común, donde mediante la aplicación de energía mecánica se elimina material de una pieza. Como toda técnica de fabricación, el mecanizado por arranque de viruta produce distintos desechos o también llamados subproductos como: virutas del metal base, fluido de refrigerante, aceite lubricante, polvo metálico y excesivo uso de energía, estos desechos tienen importantes consecuencias para el medio ambiente, por lo que las metodologías para evaluar la afectación ambiental hacen que estos procesos tradicionales sean sostenibles. **Objetivo:** El presente estudio se propone investigar cómo las innovaciones tecnológicas pueden reducir el impacto ambiental de los procesos industriales de mecanizado por arranque de viruta con tornos paralelos. **Metodología:** La metodología en la estructuración de la presente investigación corresponde a una revisión exhaustiva de la literatura, seleccionando estudios recientes de alto impacto a través de bases de datos académicas reconocidas**.** **Resultados:** Los hallazgos de este estudio destacan que el mecanizado en seco emerge como una técnica clave para eliminar la necesidad de refrigerantes líquidos, abordando así los desafíos ambientales asociados con su disposición y reduciendo la exposición a sustancias potencialmente dañinas. La micro pulverización (MQL) se identifica como una estrategia efectiva para reducir el uso de lubricantes, minimizando la contaminación y los costos operativos al tiempo que mantiene la eficiencia del mecanizado. Además, el enfriamiento criogénico destaca por su capacidad para mejorar la dureza y resistencia al desgaste de las herramientas de corte. **Conclusiones**: Se concluyó que al integrar tecnologías innovadoras como refrigeración criogénica y la MQL en el sector manufacturero no solo mejora su sostenibilidad ambiental sino también su competitividad económica, representando pasos significativos hacia la reducción de los impactos ambientales adversos de la manufactura.

Keywords: machining, starting, chips, lathes, parallels, sustainability,

Abstract

Introduction: Metal machining by chip removal is the fundamental technique in the manufacturing industry, with turning being the most common traditional machining process, where material is removed from a piece through the application of mechanical energy. Like any

cooling, cryogenics, spraying.

manufacturing technique, chip removal machining produces different wastes or also called by-products such as: base metal chips, coolant fluid, lubricating oil, metal dust and excessive use of energy, these wastes have important consequences for the environment, so the methodologies to evaluate environmental impact make these traditional processes sustainable. Objective: The present study aims to investigate how technological innovations can reduce the environmental impact of industrial machining processes by chip removal with parallel lathes. Methodology: The methodology in structuring this research corresponds to an exhaustive review of the literature, selecting recent high-impact studies through recognized academic databases. Results: The findings of this study highlight that dry machining is emerging as a key technique to eliminate the need for liquid coolants, thereby addressing the environmental challenges associated with their disposal and reducing exposure to potentially harmful substances. Microspraying (MQL) is identified as an effective strategy to reduce lubricant usage, minimizing contamination and operating costs while maintaining machining efficiency. In addition, cryogenic cooling stands out for its ability to improve the hardness and wear resistance of cutting tools. Conclusions: It was concluded that integrating innovative technologies such as cryogenic refrigeration and MQL in the manufacturing sector not only improves its environmental sustainability but also its economic competitiveness, representing significant steps towards reducing the adverse environmental impacts of manufacturing.

Introduction

Nowadays, there is a need to achieve sustainability requirements in all economic activities, especially in the industrial sector. These requirements are related to the triple bottom line of sustainability, which is based on environmental, social and economic aspects. The main sustainability requirements can be expressed in the use of renewable resources, the reduction of environmental impacts, the improvement of occupational health and personal safety, and the increase in quality of life (Salem et al., 2021).

Sustainable machining processes are characterized by the efficient use of resources, considering three fundamental aspects: economic, environmental and social. The main

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objective is to minimize harmful effects on the environment, without this meaning increasing production costs, which are very limited in the manufacturing sector (Hoghoughi et al., 2022).

The manufacturing sector is one of the most focused sectors in applying sustainability principles due to the enormous use of natural resources and harmful environmental impacts. In addition, it is considered one of the most effective contributing sectors in the development of the international economy, job creation and improvement of people's lives (Ishfaq et al., 2021).

Technically, up to two-thirds of the total energy consumed in machining operations is not utilized as it is converted to heat and the remainder is consumed by feed axes, fixtures, idle motors, controllers and other fixed electronics (Zohra et al., 2023). Statistics from the US Energy Information Administration (2020) show that energy consumption related to machining operations accounts for more than 20% of the total energy consumption of the manufacturing industry; therefore, in order to gain benefits and remain competitive, industrialists need to make more efforts to adopt strategies that can help reduce energy consumption (Hu et al., 2019).

To meet sustainability requirements in the machining industry, significant effort has been devoted to developing new machining strategies that minimize the negative environmental impacts of machining processes. These strategies, such as dry cutting, cooling/lubrication methods employing minimal amounts of cutting fluids, and cryogenic cooling, are presented as potential solutions to achieve a sustainable machining environment. On the other hand, numerous attempts have been made to assess the sustainability levels of machining processes by developing sustainability metrics (Krolczyk et al., 2019).

Although new manufacturing processes have recently emerged that revolutionize the panorama regarding the manufacture of parts, the machining process remains alive and updated in this context, always presenting itself as a manufacturing process with several variants and allowing high dimensional precision and high levels of surface finish (Kwon et al., 2020).

Sustainable machine tools offer energy savings and minimize environmental pollution. Improving the performance of components such as spindles and motors contributes to these savings. Although not initially designed with energy savings in mind, cutting tools can be optimized by changing their base material or adding special coatings, which improves their energy efficiency and effectiveness without significantly increasing costs (Kwon et al., 2020).

In fact, machining has numerous aspects that constantly need to be investigated due to the constant evolution of the materials to be machined, the materials and geometry of the tools, and the evolution of the coatings normally applied to the surfaces of the tools (Kumar et al., 2021). For example, the chips that can be formed during machining processes have been the subject of several studies because chip formation provides valuable and useful information about the manner in which the machining process is being carried out and can provide insight into issues related to chip removal from equipment and space occupied (Chen et al., 2021).

In this context, the chip removal process involves the controlled removal of material from a workpiece using cutting tools, allowing the creation of parts with complex geometries and tight tolerances. Chip removal machining includes operations such as turning, milling, drilling, and grinding, each tailored to different needs and material types (Alammari et al., 2023).

The relevance of these processes in the industrial sector cannot be underestimated, as they allow the mass production of components with high precision, which is essential for maintaining high standards of quality and performance in critical sectors of the economy. Furthermore, the flexibility of chip removal machining facilitates innovation in design and manufacturing, by allowing rapid prototyping and adaptation of components to new specifications. However, this ability to adapt and respond to changing market demands comes with challenges, especially with regard to the environmental impact of these operations (Gonçalves et al., 2020).

Machining by chip removal, although indispensable, is resource and energy intensive, and generates a significant amount of metal and chemical waste. The sustainability of this process is a growing concern, driving the search for technological and methodological innovations that can reduce its environmental footprint without compromising quality or production efficiency (Hassan, 2022).

Adopting more sustainable practices in machining is not only vital to minimise negative effects on the environment, but also to ensure the long-term viability of the industrial sector in the face of stricter environmental regulations and increased consumer ecological awareness. In this context, metal cutting is at a crossroads, with the opportunity to lead the way towards more responsible and sustainable manufacturing (Dornfeld, 2019).

Based on the above, the present study aims to review the state of the art on the reduction of the environmental impact of industrial machining processes by chip removal with parallel lathes using innovative methods.

Methodology

The state of the art represents the most advanced level of knowledge and development achieved in a specific art or technique at a given time (Corzo et al., 2022). In this context, this study adopts a descriptive research design, focused on the review of the state of the art on technological innovations in chip removal machining with parallel lathes and their impact on sustainability and energy efficiency. The research modality is non-experimental, exploratory and documentary level, since it is based on the review and analysis of existing literature, including articles from scientific journals, doctoral theses, patents and proceedings of relevant conferences in the field of engineering and sustainability (Vizcaíno et al., 2023).

The search for relevant literature was conducted in several academic databases recognized for their rigor and coverage in the field of engineering and sustainability. The databases included in this process were Scopus, Web of Science, PubMed, IEEE Xplore, as well as conference proceedings, doctoral theses, and patent records. This diversity of sources ensured a broad and deep coverage of current knowledge in the area of study.

To ensure the accuracy and comprehensiveness of the search, several combinations of keywords relevant to the topic of study were employed. Keywords included "machining", "parallel lathes", "environmental impact", "innovation in machining" and "sustainability in industrial processes". For the selection of literature, the following inclusion criteria were established:

- Recent Publications: Studies published in the last 5 years were considered to ensure the relevance and timeliness of the information.
- High Impact and Innovative Methods: Priority was given to articles in high-impact journals and studies that presented innovative methods for reducing environmental impact in machining, reflecting significant advances in the field.

Once the studies were selected through a rigorous review process based on the established criteria, the results were analysed in detail. This phase involved a thorough evaluation of the technological innovations in chip removal machining and their impact on the sustainability of industrial processes, especially in the use of parallel lathes. Particular emphasis was placed on identifying how these innovations contribute to reducing environmental impact, through improved energy efficiency, minimising the use of coolants and optimising machining processes to extend tool life and reduce waste.

Regarding ethical aspects, this study complies with international ethical regulations and guidelines for literature review; however, due to the nature of the research, authorization from institutions and scientific councils is not required.

Results

Machining operation is defined as a material removal process that involves the formation of chips, encompassing various chip morphologies such as continuous chips, continuous chips with built-up edges, discontinuous chips, and serrated chips. As cutting speed increases, the chip type varies, tending toward serrated chips due to uneven distribution of deformation and heat in the shear zone. Serrated chips are particularly problematic as they are a major source of high cyclic cutting forces, intensive tool crater wear, significantly reducing tool life, producing poor quality surface finishes, and generating vibrations (Chen et al., 2007). 2021).

Parallel lathe machining is a manufacturing process used in the mechanical industry to shape parts by removing material. This process is carried out on a machine tool called a lathe, specifically on models known as parallel lathes due to the parallel arrangement of the main axis of the machine with respect to the bed on which it is mounted (Patel & Chauhan, 2021). On the other hand, parallel machines in a production environment can be divided into three categories based on the nature of the machine: identical, uniform, and unrelated parallel machines (Lun & Liao, 2020).

There are various techniques and approaches for sustainable machining operations, since many researchers have found replacements, benefiting the health of workers, minimizing machining costs and reducing the impact on the environment, among the main ones are (Wang et al., 2023):

- Dry Machining: The absence of cutting fluids in machining is termed as dry machining, gaining prominence in the manufacturing world for its environmental friendliness, worker satisfaction, decreased coolant cost, and reduced leakage flow. An experiment conducted on compacted graphite iron for 3150 holes by drilling process has demonstrated the feasibility of dry machining, though it presents challenges such as inaccurate workpiece dimensions and reduced tool life due to high temperatures in the machining area.
- Minimum Quantity Lubrication (MQL) is defined as the mixture of compressed air and a small amount of oil in the form of fine droplets sprayed onto the cutting area. The machinability of Inconel is improved under MQL compared to dry or wet machining, with MQL and tool coating being essential factors for green manufacturing and high speed machining.
- Cryogenic Cooling: It is advantageous and sustainable in terms of protection, cleanliness and environmental friendliness. It includes approaches such as cryogenic pre-cooling of the workpiece, chip cooling, indirect cryogenic cooling and cryogenic tool cooling. It increases productivity, prolongs tool life and improves surface quality without deteriorating its mechanical or chemical

properties, being more effective than traditional lubrication and cooling methods.

- Mist Cooling Technique: Mist cooling involves dispersing a coolant liquid from a pressurized nozzle in tiny droplets onto the cooled surface, favored when flood cooling is avoided in machining, resulting in greater efficiency than flood cooling with a lower environmental impact.
- High Pressure Cooling (HPC): Used to cut hard materials, reducing tool wear and production costs. It penetrates deep into the cutting process and has a more significant cooling effect than traditional methods, reducing friction and increasing tool life.
- Hybrid Cooling/Lubrication Technology: Attempts have been made to incorporate two or three coolant solutions to enhance the effects of cooling/lubrication methods in machining operations, such as combining cryogenic and MQL techniques to improve surface roughness and tool life.

On the other hand, for Chandel et al.(2021)Among the main technological innovations related to the chip removal machining system are:

Table 1

Main technological innovations related to the machining system

Technique used	Research results
Dry machining and cryogenic cooling	Experiments are presented on Mg AZ31 B alloy with dry machining and cryogenic cooling. Cryogenic machining will increase the surface integrity of the workpiece while also improving the machining efficiency.
Dry machining, flooded coolant and cryogenic cooling	Experiments were conducted on Ti-6Al-7Nb under various cooling environments including dry machining, flooded coolant and cryogenic cooling. It was revealed that the cutting force and thrust force were reduced by 30% when machined with MQL, flooded.
Cryogenic cooling	The experiment was carried out on AISI 4340 steel workpiece using cryogenic cooling machining technique. It was observed that the Ra error is only 5.32%.
Dry machining and cryogenic cooling	The research work was carried out on duplex stainless steel 2205 under dry machining and cryogenic cooling conditions. As a result, the cutting temperature was reduced and the cutting power was 53–58%, in contrast to dry machining, the roughness was improved by 18–23%.
Machining in dry atmosphere and cryogenic cooling	In this article, dry atmosphere machining and cryogenic cooling environment were used on AISI 52,100 steel workpiece. It was found that cryogenic machining produced the best results.
Cryogenic cooling	Experiments were conducted on Ti-6Al-4V in treated and untreated environments (24H, 48H). As a result, 24H, 48H produces the best effects and reduces vibration compared with untreated.
Dry machining, pure MQL, LN2, Nmql, cryMQL and cry-Nmql	This article discusses the machining of Inconel 625 under various cooling environments including dry machining, pure MQL, LN2, Nmql, cry-MQL and cry-Nmql. It was found that using a 0.5 vol% hbn cooling system with LN2 provided the best results in machining efficiency such as tool life, Ra.
MQL	Experiments on Ti-6Al-4 V under flood cooling, supercritical CO2 and supercritical CO2 with MQL are discussed in this paper. This investigation

	revealed that ScCO2 + MQL improved tool life by 163% at V-60, f-0.5 mm/tooth.
Dry machining (untreated) and cryogenic cooling	The study on Ti-6Al-4 V under various cooling environments, such as dry machining (untreated) and cryogenically treated conditions, was presented (12H, 24H, and 36H). It was revealed that deep cryogenic treatment up to 36 h is the most reliable and reduces tool wear rather than other methods.

Fountain: Chandel et al. (2021)

The review of the state of the art in chip removal machining technologies reveals a clear orientation towards improving sustainability and efficiency in manufacturing processes. The studies analyzed, including those carried out by Chandel et al. (2021), as well as research by other authors such as Salem et al. (2021), Ishfaq et al. (2021) and Krolczyk et al. (2019), converge in the identification of innovative strategies such as dry machining, minimum quantity lubrication (MQL), and cryogenic cooling, which are presented not only as potential solutions to minimize environmental impact but also to optimize energy consumption and prolong tool life. These techniques, by reducing the dependence on traditional coolants and lubricants, directly address the challenges imposed by the need for greener practices in the manufacturing industry.

In this regard, the following describes how the aforementioned technologies can be used in chip removal machining with parallel lathes to improve sustainability:

- Dry Machining: By eliminating the use of liquid coolants, dry machining reduces the need to manage and dispose of potentially environmentally harmful chemicals. Not only does this decrease water and soil pollution, but it also reduces worker exposure to these chemicals. Additionally, by avoiding the use of coolants, companies can save on the costs of purchasing, storing, and treating these fluids, thereby promoting cleaner, more sustainable manufacturing.
- Cryogenic Cooling: Using low-temperature gases to cool the cutting zone minimizes the need for oil-based coolants, contributing to less environmental pollution. In addition, cryogenic cooling improves the efficiency of the machining process, resulting in less waste and reduced energy consumption. By extending the life of cutting tools, this technology also decreases the need for frequent replacements, thereby reducing metal waste and resource consumption.
- Flooded Coolant and MQL (Minimum Quantity Lubrication): Using only a minimal amount of lubricant, MQL technology dramatically reduces the amount of liquid waste generated compared to traditional cooling systems. This not only means less environmental pollution but also a reduction in reliance on petroleum-based lubricants, contributing to greener manufacturing. On the other hand, flooded coolant systems, when used in a

controlled manner, can optimize fluid usage, increasing efficiency while minimizing waste.

- Specific Applications such as LN2, Nmql, cry-MQL and cry-Nmql: These innovative approaches combine the benefits of cryogenic cooling with the efficiency of minimum lubrication, offering a highly sustainable solution for machining. By significantly improving process efficiency and reducing tool wear, these techniques decrease overall resource consumption, including the energy required for machining and the amount of materials consumed. Furthermore, by limiting the use of conventional lubricants and coolants, they contribute to a further reduction in environmental pollution.

However, the practical and economic context in which these technologies are applied must be taken into account. Since, while the environmental and efficiency benefits are clear, the implementation of these innovations faces barriers related to initial costs, the need for technological adaptation and personnel training. Furthermore, chip analysis in machining, as highlighted by Chen et al. (2021), provides valuable information on the effectiveness of these processes, suggesting that chip behavior can be a critical indicator of machining efficiency and surface finish quality. This aspect underlines the importance of considering not only the environmental and energy benefits of technological innovations but also their impact on production quality and operability in the industrial environment.

The scope of the results obtained highlights the potential of technological innovations, such as dry machining, minimum quantity lubrication (MQL), and cryogenic cooling, to significantly contribute to sustainability and energy efficiency in the machining sector. These technologies offer avenues to reduce waste generation, minimize energy consumption, and extend tool life, which aligns with the goals of reducing environmental impacts and improving occupational health and personal safety. In addition, the analysis of chip behavior and the evaluation of cooling and lubrication methods offer valuable insights into how to improve machining processes to achieve high levels of quality and dimensional accuracy.

On the other hand, the results are also accompanied by significant limitations, one of the main ones being the variability in the applicability of these technologies in different industrial contexts. For example, the cost and complexity of implementing cryogenic cooling systems may not be feasible for small and medium-sized companies due to limitations in capital and technical expertise. Another limiting aspect is the availability of long-term comparative data that assess the real impact of these technologies on the overall sustainability of manufacturing processes. Most studies focus on short-term results or laboratory conditions, which may not fully reflect the challenges and benefits in a real production environment.

Conclusions

- It can be concluded that the findings of this study provide insight into how the implementation of techniques such as dry machining, minimum quantity lubrication (MQL) and cryogenic cooling not only address current environmental imperatives, but also offer a route towards resource optimization and energy efficiency in manufacturing processes, without excessively increasing the costs of machining processes.
- It can be established that through the evaluation of these technologies it is possible to achieve a balance between efficient production and environmental responsibility, which constitutes a fundamental contribution to science and industrial practice, since this study reveals that the adoption of innovations is not only viable but also beneficial from a sustainability perspective, directly contributing to the reduction of the ecological footprint of the manufacturing sector.
- It can be concluded that the application of innovative technologies in machining processes with chip removal not only offers sustainable and efficient solutions to the current challenges of the manufacturing industry, but also marks a path towards the significant reduction of the environmental footprint associated with machining. The integration of these findings contributes to scientific and technological progress in the field of machining, providing a solid basis for the development of greener and more efficient practices in the industry, aligned with the principles of sustainability and environmental responsibility.
- Finally, it can be established that, through a review of the state of the art, the reduction of the environmental impact of industrial machining processes by chip removal with parallel lathes through innovative methods such as dry machining, minimum quantity lubrication (MQL), and cryogenic cooling, demonstrating their effectiveness in minimizing waste, reducing energy consumption and prolonging the useful life of cutting tools.

Conflict of interest

The author declares that there is no conflict of interest in relation to the submitted article.

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