UDC 621.914 **doi: 10.20998/2078-7405.2024.101.05**

PROGRESS AND CHALLENGES IN PLUNGE MILLING: A REVIEW OF CURRENT PRACTICES AND FUTURE DIRECTIONS

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Received: 23 October 2024 / Revised: 14 November 2024 / Accepted: 27 November 2024 / Published: 15 December 2024

Abstract. *This review examines recent advancements and ongoing challenges in plunge milling. It is an increasingly utilised machining process renowned for its high material removal rates, particularly with hard-to-machine materials like hardened steels and titanium alloys. Plunge milling's unique perpendicular tool path offers enhanced stability and reduced lateral cutting forces, making it valuable for applications that demand precision and efficiency, such as aerospace and automotive manufacturing. The paper systematically analyses and synthesises research on critical areas of plunge milling optimization, including tool geometry, material selection, coating technologies, and process parameters, highlighting strategies to mitigate common issues like rapid tool wear and chip evacuation difficulties. In this comprehensive overview, the review introduces theoretical and experimental findings on optimizing plunge milling tools and process parameters—such as cutting speed, feed rate, and coolant delivery—that are essential for improving performance and achieving desirable surface finishes. The paper also explores innovative trends, including AI-driven optimization algorithms and hybrid machining systems, which hold promise for addressing persistent limitations and enhancing plunge milling's industrial applicability. By consolidating findings from recent studies, this review contributes to a deeper understanding of plunge milling's role in high-precision manufacturing and identifies future research directions for advancing the process. The insights presented offer practical and strategic implications, aiming to guide ongoing developments in plunge milling technology and its adoption across various precision-oriented industries.*

Keywords: *Plunge milling; material removal; tool optimization; cutting tool coatings.*

1. Introduction

The role of machining in modern manufacturing cannot be overstated. It enables the production of complex, precise components across various industries [1-3]. Among the diverse machining techniques, milling has remained a staple, particularly in aerospace, automotive, and tooling sectors, where precision and efficiency are paramount [1]. Traditional methods like end and face milling typically involve sweeping the tool horizontally across the workpiece, making them effective but sometimes less efficient for high-volume material removal [2].

Plunge milling has emerged as a powerful alternative, especially for machining hard materials such as titanium alloys and hardened steels [3].

Characterized by a unique vertical, perpendicular tool path, plunge milling distinguishes itself by moving directly downward into the material, substantially improving tool stability and cutting efficiency [4]. This approach minimizes lateral cutting forces, extending tool life and reducing the likelihood of tool deflection—a benefit crucial for applications requiring deep cavity cuts or roughing operations. The technique's effectiveness has been demonstrated in demanding applications like the production of Kaplan turbine blades, where removing material rapidly without compromising precision is essential [5].

Beyond its practical benefits, plunge milling has prompted extensive research efforts to optimize tool geometry, material selection, and process parameters, including coating technologies and cutting speeds. However, challenges persist, particularly in managing rapid tool wear and optimizing chip evacuation [6,7]. This review synthesizes current advancements and presents a detailed analysis of optimization strategies, exploring emerging technology systems. By addressing these critical factors, plunge milling will continue evolving, meeting the growing demands of high-precision, high-efficiency manufacturing environments.

2. A Comprehensive Exploration

Precision milling hardened steel components, such as dies, molds, and press tools, often rely on monolithic milling cutters [8]. In this context, plunge milling has gained significant attention due to its ability to produce complex shapes and intricate features [2] accurately. Driven by the need for greater productivity, high-speed machining has also gained traction across industries [1]. This approach typically uses small feed per tooth and minimal pick feed, which effectively produce precise surface textures and are widely adopted for end-milling operations in manufacturing die/mold components and precision mechanical parts [7,9]. For milling complex surfaces, specific parameters, like axial cutting depth, play a critical role in ensuring surface quality and dimensional accuracy [8],10]. Furthermore, advancements in tool steel properties have supported the broader adoption of plunge milling, as these developments enable achieving a high surface hardness while maintaining a softer core structure advantageous for applications such as machinery parts and specialty fasteners [11,12]. The precision and adaptability of plunge milling make it an effective technique for accurately producing complex shapes and narrow apertures, enhancing its relevance across manufacturing sectors focused on intricate part production [13-15].

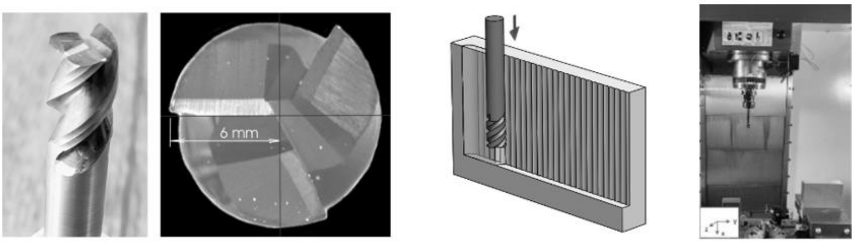
3. Process Optimization of plunge milling

3.1. Cutting tool optimization

Tool optimization is essential in plunge milling, where high mechanical stresses and thermal loads, especially with rugged materials, impact cutting efficiency, tool life, and overall performance. Adjusting tool geometry and material selection is critical to these improvements [1]. In particular, tool failure due to wear is a significant concern that requires carefully selecting cutting parameters, cooling strategies, and tool designs [6].

3.1.1. Optimization of Tool Geometry

The geometry of a cutting tool plays a critical role in plunge milling, particularly in how it handles cutting forces and heat generation. Key geometric aspects include the rake angle, clearance angle, and cutting-edge shape [2]. Plunge milling tools typically feature a positive rake angle to reduce cutting resistance and a large clearance angle to facilitate better chip evacuation, thereby minimizing the risk of tool clogging. A study by Ding et al. [16] showed that optimizing the cutting-edge radius and tool profile can significantly reduce tool wear by distributing cutting forces more evenly across the tool surface [6]. This is particularly important for maintaining tool stability during the high-impact forces of plunge milling, as shown in Figure 1 [7].



(a) (b) (c)

Figure 1. Used cutting tool, the strategy scheme, and Machining setup [7].

Edge Preparation: To reduce wear, the cutting-edge plunge milling tools can be tailored with micro-polishing or edge rounding techniques. These techniques help prevent chipping and fracture, which are common issues in plunge milling due to the aggressive vertical plunge of the tool into the material [6].

Corner Design: Tools used in plunge milling often have rounded or chamfered corners to increase strength and prevent the tool from fracturing at the corners under heavy loads. However, the tool tip's rounded corners can wear significantly during plunge milling, leading to potential failure. Common wear types include crater, flank, and notch wear. Understanding these can enhance tool life and performance, as is shown in Figure 2 [6]. Optimizing tool geometry increases tool life and improves chip formation and surface finish [7]. Effective chip evacuation is critical in plunge milling. Chips generated during the plunge motion can obstruct the tool path, leading to tool damage and poor surface quality [4,5].

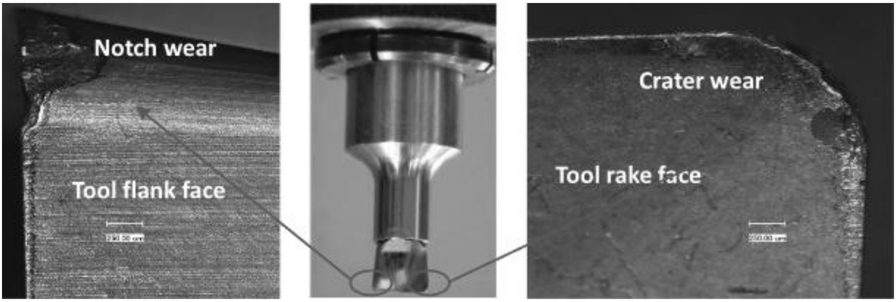


Figure 2. Plunge tool wear morphology [6].

3.1.2 Optimization of the Cutting Tool Design

The tools used in plunge milling have distinct features compared to those used in other techniques. Plunge milling cutters are designed with robust cutting edges and reinforced corners to handle the high stresses generated during vertical cutting. Due to their strength and heat resistance, these tools are typically made from carbide or high-speed steel (HSS) [2, 17]. Cutting tool design plays a critical role in the efficiency and performance of plunge milling operations. Recent advancements in materials technology, as is shown in Figure 3, have enabled the development of high-strength and ultra-hard materials that are challenging to machine using conventional methods [18–20]. Appropriate selection is also crucial in plunge milling, as it directly impacts the tool's wear resistance, thermal stability, and overall service life [6, 21, 22]. Cemented carbide, diamond-coated tools, and polycrystalline diamonds are among the materials extensively studied for their suitability in applications [8, 17, 23]. Recent research has focused on material selection and the optimization of cutter geometry. Investigations into the effects of axial and radial rake angles and the impact of interference during helical milling have provided valuable insights into the design of high-performance milling cutters [10, 22, 24, 25].

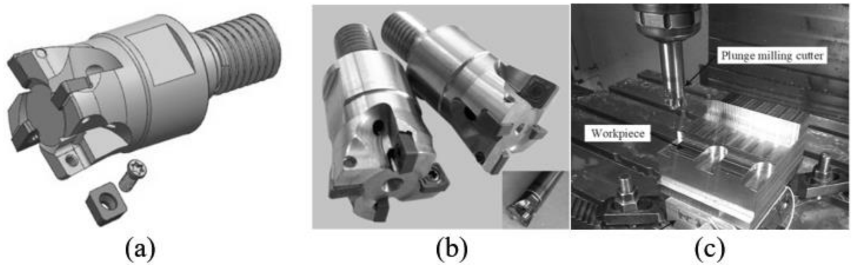


Figure 3. Optimizing the (a) Design, (b) Manufactured, (c) Experiment, plunge milling cutting tool [20].

3.1.3. Optimizing Cutter Geometry and Material Selection

Due to the significant differences in scale, traditional design methods for milling cutters are no longer applicable to micro-scale tools [26], [27]. Researchers have explored new micro-mill design approaches to address this challenge, focusing on optimizing cutting processes and integrating them with the tool design process, as shown in Figure 4 [21, 28]. One such approach is the development of parametric design systems for micro-mills, which leverage computer-aided design tools and programming techniques to establish a flexible and accurate tool design process [29–31]. This enables the creation of customized tool designs tailored to specific machining requirements by deconstructing the geometric features of micro-mills and connecting them through expression functions [1, 32, 33].

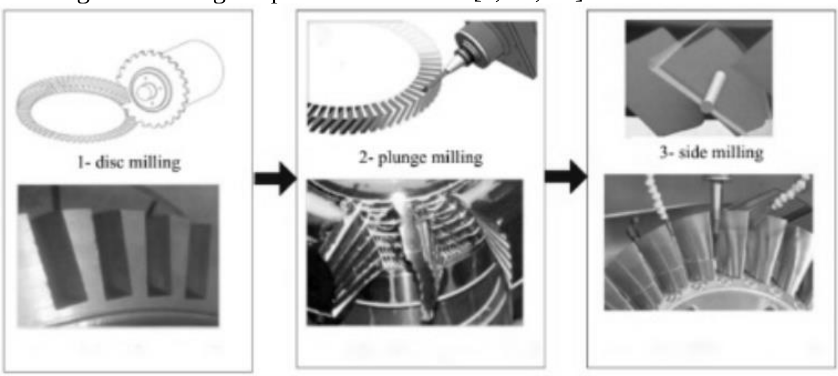


Figure 4. Optimizing cutting processes in plunge milling [28].

3.2. Tool Materials and Coatings Optimization

The choice of tool material is critical to ensuring high-performance plunge milling. Cemented carbide is the most commonly used material for plunge milling tools due to its high hardness and wear resistance [7, 23]. High-speed steel (HSS) is also used in some applications, though it is less wear-resistant than carbide [17, 34]. In recent years, research has focused on advanced coatings to enhance tool performance further [35, 36]. Coated carbide tools have significantly improved wear resistance and thermal stability compared to uncoated tools. Typical coating materials include:

– Titanium Nitride (TiN) is a widely used coating that provides wear resistance and reduces friction during cutting [37, 38]

– (Sweatt et al., 2008) Titanium Aluminum Nitride (TiAlN) offers superior oxidation and thermal degradation resistance, making it ideal for high-speed plunge milling in materials that generate significant heat during cutting [7, 34, 39].

– **Diamond-like Carbon (DLC) Coatings**: These coatings provide extreme hardness and low friction, improving tool life when machining abrasive materials like composites and hardened steels [1, 40]. Zagórski et al. show that TiAlN coatings, especially with AlTiN, enhance plunge milling by creating a thermal barrier that reduces adhesive wear and stabilises cutting forces. TiAlN-coated tools lower cutting forces under high-speed machining (HSM) conditions, boosting tool durability and milling efficiency in demanding applications [34, 41].

3.3. Process Parameter Optimization

Optimizing cutting parameters such as cutting speed, feed rate, and depth of cut is essential for minimising tool wear and maximising machining performance [1, 2]. Finite Element Modeling (FEM) has become a vital tool in predicting how different cutting parameters affect tool performance in plunge milling. By simulating the forces, temperatures, and stresses acting on the tool during machining, FEM helps identify the optimal cutting conditions that will reduce wear while maintaining high MRR [21, 42, 43].

– Cutting Speed: Increasing the cutting speed improves MRR but generates more heat, leading to thermal wear. Balancing speed with appropriate cooling strategies is critical for maintaining tool life [5, 12, 44].

– **Feed Rate:** High feed rates lead to increased cutting forces, which can cause tool deflection and wear. Optimizing the feed rate helps maintain tool stability and reduces cutting-edge chipping [6, 12, 45].

– Depth of Cut: In plunge milling, the cut's depth directly affects the tool's load. Guo et al. found that reducing the cut depth in combination with coated tools can significantly lower tool wear, especially when machining hard materials like Inconel and titanium alloys [1, 20].

– Workpiece Materials and Geometries: Advances in materials technology have led to the development of high-performance composites, ceramics, and other difficult-to-machine materials, which pose unique challenges for conventional machining [1, 24]. Plunge milling has emerged as a viable solution for effectively machining these advanced materials. It leverages the direct application of energy to remove material without the limitations of traditional chip-removal methods [2]. The geometry of the workpiece, as shown in Figure, can significantly impact the tool path planning, cutter accessibility, and overall machining efficiency [1, 26, 46]. Research has explored using CAD-based visualization techniques and cutter accessibility maps to optimize the process for complex workpiece geometries, such as those encountered in the aerospace and automotive industries [2, 26, 47, 48]

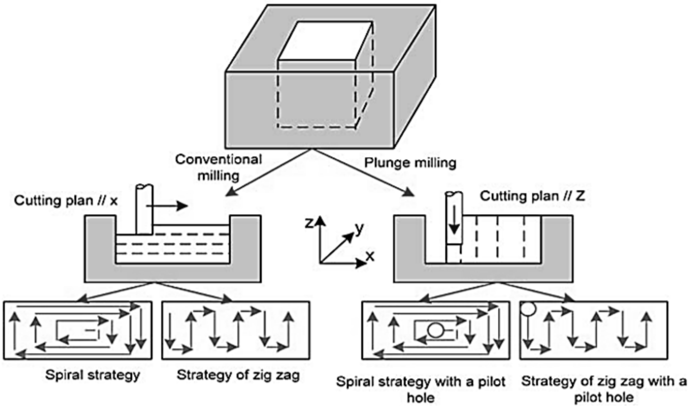


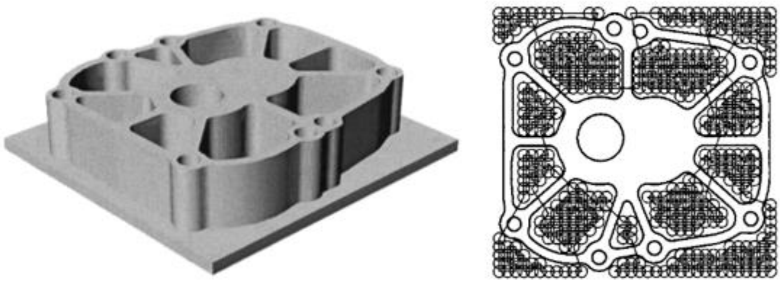
Figure 5. Machining strategies [26].

3.4. Optimized Chip Management and Coolant Delivery:

In plunge milling, efficient and coolant delivery is vital due to the high intensity cutting process that can result in rapid chip accumulation [18, 19]. Researchers have developed innovative methods such as air-jet-assisted chip removal, high-pressure coolant systems, and optimized tool geometries. These techniques significantly improve chip evacuation, preventing tool interference, machine damage, and surface quality degradation [7, 19]. Moreover, cutting fluid and coolant delivery is crucial in plunge milling to extend tool life, avoid thermal damage, and preserve surface integrity [23, 49]. Advanced fluid delivery techniques, like minimum quantity lubrication (MQL) and cryogenic cooling, have been investigated to optimize cooling and lubrication. These advanced methods can enhance stability and improve surface quality and efficiency [35, 50].

3.5. Optimization Algorithms for Plunge Milling

Optimizing operations is a complex task that requires considering various parameters, including tool geometry, material properties, and process conditions [29, 51]. Recent research has focused on developing advanced Optimization to improve the efficiency and productivity of plunge milling [52, 53]. These algorithms leverage computational models and simulation tools to predict and analyze the performance of plunge milling processes, enabling the selection of optimal cutting parameters, tool paths, and machining strategies, as shown in Figure 6 [1, 54, 55, 56,58]. Integrating these Optimization algorithms with CAD/CAM systems has further enhanced plunge milling capabilities, allowing for the integration of design, planning, and machining operations [51, 54, 55, 57].



(a) (b)

Figure 6. (a) Rendering of CAD drawing, (b) toolpoint path design(right) for a plunge milling example[58].

4. Advantages of plunge milling:

Plunge milling stands out in industrial machining for its high material removal rates (MRR), improved productivity, and efficient chip evacuation [1, 12, 59]. It is ideal for applications like mold and die-making, where precision is paramount [21, 28]. Unlike conventional methods, plunge milling directs the tool vertically into the material, reducing machining time and generating less heat, which extends tool life and enhances surface finish [55, 60]. It minimizes issues like tool deflection and vibration, allowing for better dimensional accuracy and control over the cuts, which is critical in complex geometries and intricate designs [22, 61]. Plunge milling enables advanced strategies like trochoidal tool paths and high-speed machining, reducing cutting forces and vibrations, enhancing tool life, and improving efficiency [1, 5]. Optimal parameters—such as cut depth and feed rate—help prevent surface and subsurface defects, especially in sensitive materials [4]. Its force control, tool stability, and cost-effective precision make plunge milling suitable for complex, high-tolerance designs across industries [4, 41, 62].

5. Challenges and Limitations / Current Challenges:

Critical challenges include rapid tool wear when machining superalloys, di-chip evacuation, and high tool costs [4, 20]. Grzesik et al. identified the need for better materials and cooling strategies to overcome limitations [5, 1].

5.1. Barriers to Adoption:

The high initial cost of specialised plunge milling tools and the complexity of process Optimization have limited its adoption in smiles [4,1]. She pointed out the need for cost-effective solutions.

5.2. Technical challenges:

Tool wear, particularly when machining abrasive materials, remains a significant challenge in plunge milling [27, 63]. Herbert et al. address the challenge of achieving near damage-free surfaces while minimising material removal during finishing operations [64], which can lead to cost savings and improved efficiency in manufacturing processes [4, 46].

5.3. Material-specific challenges:

Plunge milling of superalloys such as titanium poses heat generation and tool life challenges. Due to machine capacity or tool wear, high-temperature alloys and lightweight materials may limit high-speed machining and high-performance cutting [63, 65].

5.4. Surface quality and integrity:

Ensuring high-quality and consistent surface finish and integrity is crucial for the long-term performance of some components [51, 66]. Xin et al. note that multi-milling technology can increase cutting forces and vibrations, leading to surface defects like burrs, scratches, and micro-cracks that may weaken blisks over time by creating stress concentrators [28, 51, 66]. Guo et al. discovered that using the wavy-edge cutter reduced vibration amplitude by over 90% and cutting force by about 50% compared to straight-edge cutters [20].

6. Future Trends and Research Directions

6.1. Smart Machining Systems:

The study mentions the use of AI technology in intelligent machining, which includes various applications such as Optimization of machining parameters, real-time monitoring, and process control [21]. Hashmi et al. integrate sensors and AI in plunge milling to improve efficiency. Accelerometers on the spindle head measure forces, while AI processing detects and mitigates chatter, boosting material removal rates (MRR) and reducing machining time [64, 67]. Exploring advanced techniques to further optimise the tool path planning process, improve the selection of optimal plunger centres, and adapt the approach to various manufacturing scenarios [68].

6.2. Hybrid method:

Researchers have explored enhancing plunge milling's capabilities by combining it with high-speed milling, laser-assisted machining, and additive manufacturing [1], which improve surface finish, boost material removal rates, and allow component repair or modification [64]. Effective integration requires advanced process planning, control algorithms, and coordination of multiple machining systems [42]. Xni et al. present a multi-milling technology for blisk processing that combines disc, plunge, and side milling to boost efficiency and reduce costs. Simulations reveal a 91.2% material removal rate, surpassing plunge and side milling (86.5%) and side milling alone (81.8%) [28, 51]. Omari et al. demonstrated that the Medial Axis Transformation can improve machining efficiency by expanding the milling area and converting shapes into efficient, tree-like structures for easier manipulation [31]. Also, using multi-axis milling machines could potentially revolutionise complex layered contour plunging processes, further enhancing the efficiency of plunge milling [31, 42, 69, 22].

6.3. Tool material development:

Future advancements in tool materials will likely focus on hybrid composites and nanostructured coatings for improved durability and performance [7, 42]. Researchers focus on eco-friendly, energy-efficient plunge milling practices such as alternative cutting fluids, optimised energy use, and dry machining to reduce environmental impact, resource use, and costs while ensuring quality and productivity [1, 4].

6.4. Sustainability and Eco-Friendly Approach

Altıntaş et al. developed a model to predict and reduce energy consumption in milling, aiding sustainable manufacturing through energy-efficient process planning and parameter selection [27, 70]. Therefore, the study implicitly supports the idea that Optimizing milling contributes to sustainability goals [52]. Researchers aim to enhance machining while minimising the environmental impact, carbon emissions, and production costs associated with the grinding process [4, 51]. Awale et al. examine the grindability of AISI H13 tool steel using eco-friendly nano-lubricants under minimum quantity lubrication (MQL), aiming to enhance sustainability in tooling by improved surface integrity, reduced energy consumption, carbon emissions, and cost savings [50].

7. Conclusion

This review highlights plunge milling as a valuable machining method that enables high-efficiency material removal in hard-to-machine materials. By emphasising vertical cutting, plunge milling achieves significant improvements in tool stability and force reduction, proving especially beneficial for intricate and high-precision applications. Through an analysis of the latest research, this paper presents advancements in tool design, material selection, and process Optimizations that collectively address core challenges, such as tool longevity and effective chip evacuation. The findings underscore that, while plunge milling has established its place in the industry, continued research is essential to unlock its full capabilities and overcome existing limitations. This review provides a consolidated resource for current practices and future directions, supporting the evolution of plunge milling into a more versatile and sustainable manufacturing solution.

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ПРОГРЕС І ПРОБЛЕМИ ВРІЗНОГО ФРЕЗЕРУВАННЯ: ОГЛЯД ПОТОЧНОЇ ПРАКТИКИ ТА МАЙБУТНІХ НАПРЯМКІВ

Анотація. *У цьому огляді літератури розглядаються останні досягнення та поточні проблеми в врізного фрезерування. Це все більш часто використовуваний процес обробки, відомий своєю високою швидкістю видалення матеріалу, особливо з важкооброблюваними матеріалами, такими як загартовані сталі та титанові сплави. Унікальна перпендикулярна траєкторія інструменту врізного фрезерування забезпечує підвищену стабільність і зменшує поперечні сили різання, що робить його цінним для застосувань, які вимагають точності та ефективності, таких як аерокосмічне та автомобільне виробництво. У статті системно аналізуються та узагальнюються дослідження з критично важливих областей оптимізації врізного фрезерування, включаючи геометрію інструменту, вибір матеріалу, технології покриття та параметри процесу, висвітлюючи стратегії пом'якшення поширених проблем, таких як швидкий знос інструменту та труднощі з евакуацією стружки. У цьому всеосяжному огляді в огляді представлені теоретичні та експериментальні висновки щодо оптимізації інструментів для врізного фрезерування та параметрів процесу, таких як швидкість різання, швидкість подачі та подача охолоджуючої рідини, які мають важливе значення для підвищення продуктивності та досягнення бажаної обробки поверхні. У статті також досліджуються інноваційні тенденції, включаючи алгоритми оптимізації на основі штучного інтелекту та гібридні системи обробки, які є перспективними для вирішення постійних обмежень і підвищення промислової застосовності врізного фрезерування. Узагальнюючи результати нещодавніх досліджень, цей огляд сприяє глибшому розумінню ролі врізного фрезерування у високоточному виробництві та визначає майбутні напрямки досліджень для вдосконалення цього процесу. Представлені ідеї мають практичні та стратегічні наслідки, спрямовані на спрямування поточних розробок у технології врізного фрезерування та її впровадження в різних галузях, орієнтованих на точність.*
Ключові слова: *врізне фрезерування; видалення матеріалу; оптимізація інструменту; покриття ріжучого інструменту.*