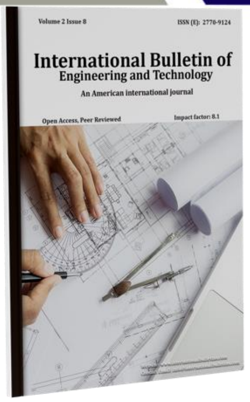

INVESTIGATION OF SURFACE INTEGRITY AND RESIDUAL STRESSES IN MACHINING OF DIFFICULT-TO-CUT MATERIALS

Tuyboyov Oybek Valijonovich [1]
Toshtemirov Kamol Qahramonovich [2]
Toshtemirova Gulnora Ayubjonovna [3]
[1] Tashkent State Technical University, Associate Professor of the Department of Mechanical Engineering (Uzbekistan)
[2] Almalik State Technical University, Senior Lecturer of the Department of Mechanical Engineering (Uzbekistan)
[3] Almalik State Technical University, assistant of the Department of Mechanical Engineering (Uzbekistan)
https://doi.org/10.5281/zenodo.11503517

ABSTRACT

Machining advanced materials presents significant challenges due to severe tool wear and high cutting forces. This paper discusses emerging technologies such as selective melting, laser-assisted machining, and diamond wire saw machining, which offer promising solutions for effectively cutting these materials while maintaining precision and surface integrity. Advancements in micro milling techniques also contribute to machining difficult-to-cut materials. Challenges associated with superalloys, composite materials, and ceramic matrix composites include high tool wear and intricate material removal mechanisms, leading to surface defects. Researchers focus on improving tool life, surface integrity, and machining quality through tool modifications, cooling techniques, and optimizing machining parameters. Innovative techniques like natural fiber composites and minimum quantity lubrication aim to enhance machinability sustainably. Understanding surface integrity and residual stresses is crucial, with predictive models essential for optimizing machining processes. Experimental methodology involves designing experiments to study surface integrity and residual stresses, while finite element analysis aids in predicting critical parameters during machining. Results demonstrate significant improvements in surface roughness, material removal rates, and machinability through advanced techniques and strategic modifications. The integration of finite element analysis enhances machining simulations, offering valuable insights for optimizing processes. In conclusion, embracing innovative techniques and materials improves machinability while promoting sustainability, addressing the evolving needs of modern manufacturing.

Keywords: *Machining, Advanced materials, Tool wear, Surface integrity, Machinability, Finite element analysis, Micro milling, Cooling techniques, Residual stresses, Sustainability*

INTRODUCTION

These materials pose challenges in machining processes due to severe tool wear and high cutting forces involved. Technologies like selective melting, laser-assisted machining [1], and diamond wire saw machining have emerged as promising solutions for effectively cutting these materials while maintaining high precision and surface integrity. The advancements in micro milling techniques have also contributed to the machining of difficult-to-cut materials [2], offering opportunities for further developments in this field. Challenges associated with machining advanced materials like superalloys, composite materials, and ceramic matrix composites include high tool wear due to their heat sensitivity and aggressive fibers [3]. The intricate nature of these materials results in various material removal mechanisms, causing surface defects and compromising product quality. To address these challenges, researchers focus on improving tool life, surface integrity, and machining quality through methods like tool modifications, cooling techniques, and optimizing machining parameters. Additionally, the use of innovative techniques and materials like natural fiber composites [4] and minimum quantity lubrication aims to enhance machinability while maintaining cost-effectiveness and sustainability. Understanding surface integrity and residual stresses is crucial for ensuring component reliability and performance. Experimental determination of these parameters is challenging and destructive, making predictive models essential for optimizing machining processes and material performance. Techniques such as finite element modeling, micromagnetic, and ultrasonic methods enable non-destructive evaluation of residual stresses at different scales and depths, aiding in managing stress conditions to prevent premature failures. Moreover, understanding the effects of residual stresses on structural integrity, creep behavior, and crack initiation is vital for accurate reliability assessments and optimizing component lifetime under various loading conditions.

These materials often lead to poor machinability due to factors like accelerated tool wear, reduced productivity, and increased production costs. The low thermal conductivity of difficult-to-cut materials concentrates heat in the cutting zone, causing rapid tool deterioration and issues like thermal errors and low dimensional accuracy. Additionally, the use of cutting oils, both water soluble and insoluble, affects machinability by influencing tool-flank [5] temperature and cutting forces during milling processes. Additionally, the geometry of the cutting tool, including point and clearance angles, plays a vital role in achieving effective machining without the need for internal cooling. Furthermore, the edge geometry of cutting inserts and process parameters affect the topographical characteristics of machined surfaces, with feed rate being a key influencing factor. Material removal during machining involves various mechanisms influenced by factors like power, energy distribution, and tool characteristics. In grinding processes, high-speed abrasive tools define material removal mechanisms, with sharp tools leading to low forces and power requirements. Electrical discharge machining (EDM) [6] utilizes rapid local heating to detach material clusters, leading to melting and vaporization, generating high pressures for material ejection. Fast EDM benefits from high-pressure flushing [7] to enhance material expulsion efficiency, with excessive heat convection reducing machining effectiveness. Machining hard tissues like bone involves managing high cutting forces and temperatures to prevent necrosis and microcracks, crucial for surgical success and recovery. Understanding these material removal mechanisms and heat generation processes is essential for optimizing machining efficiency and minimizing damage in various machining applications. Experimental methodology in machining involves designing experiments to study surface integrity and residual stresses. Workpiece materials and cutting tools selection is crucial, impacting outcomes. Measurement techniques like X-ray diffraction and hole-drilling method assess residual stresses [8], while surface integrity is evaluated through surface roughness and microstructure analysis. Understanding the principles of experimental research is essential for conducting valid studies in machining processes.

Surface integrity analysis involves evaluating surface roughness and morphology pre and post-machining to ensure optimal component performance [9]. Various factors like cutting parameters, tool characteristics, and material properties influence surface quality. Studies show that surface roughness significantly impacts contact performance, with increased roughness leading to higher contact deformation but opposite trends in contact stress, stiffness, and area. Understanding these factors and employing appropriate optimization methods can enhance surface integrity and overall component reliability. Cutting parameters and tool characteristics play a crucial role in determining the final surface integrity. Research on Ti-6Al-4V alloy machining reveals that cutting speed [10] and feed rate influence the formation of transformed layers and localized plastic deformation on the machined surface. Tool wear during turning of titanium alloy leads to altered microstructures, with increased plastic activities and grain distortions, affecting surface quality. Additionally, the study of ultrasonically assisted cutting (UAC) compared to conventional cutting (CC) shows that UAC induces less pronounced microstructural changes, highlighting the importance of tool wear optimization for improved surface integrity [11]. Residual stress characterization methods vary based on material types and processing techniques. Techniques like micro-grinding induce residual stresses influenced by material microstructure and mechanical loading. Mapping residual stress distribution across machined surfaces involves experimental verification and numerical modeling, considering thermal gradients and plastic deformation effects. Residual stresses are correlated with machining-induced microstructural alterations, with studies focusing on plastic deformation and rate-independent behavior in composites. Overall, understanding residual stress distribution and its correlation with microstructural changes is crucial for optimizing machining processes and reducing distortion in manufactured components. Finite Element Analysis (FEA) [12] modeling in machining processes allows for predicting temperature distribution, chip formation, and residual stress evolution. Studies have utilized FEA with material constitutive models like Johnson–Cook and Usui, along with tool wear models, to simulate machining of various materials such as titanium alloys and steels. The integration of FEA in machining simulations provides insights into optimizing tool geometry, processing parameters, and enhancing machining efficiency by accurately predicting and analyzing the complex phenomena occurring during cutting processes.

METHODS

Figure. 1 illustrates the comparison of surface roughness measurements before and after machining using two advanced techniques: selective melting and laser-assisted machining. Surface roughness is an important parameter in machining processes as it directly affects the quality and functionality of machined components. Lower surface roughness values indicate smoother surfaces, which are desirable in many engineering applications. Before machining, the surface roughness measurements represent the initial state of the workpiece. As seen in the plot, the surface roughness values before machining (depicted in blue) are relatively higher compared to the values after machining using advanced techniques. After machining using selective melting (depicted in red), and laser-assisted machining (depicted in green), the surface roughness values significantly decrease. This reduction in surface roughness highlights the effectiveness of these advanced machining techniques in improving surface finish and achieving smoother machined surfaces.

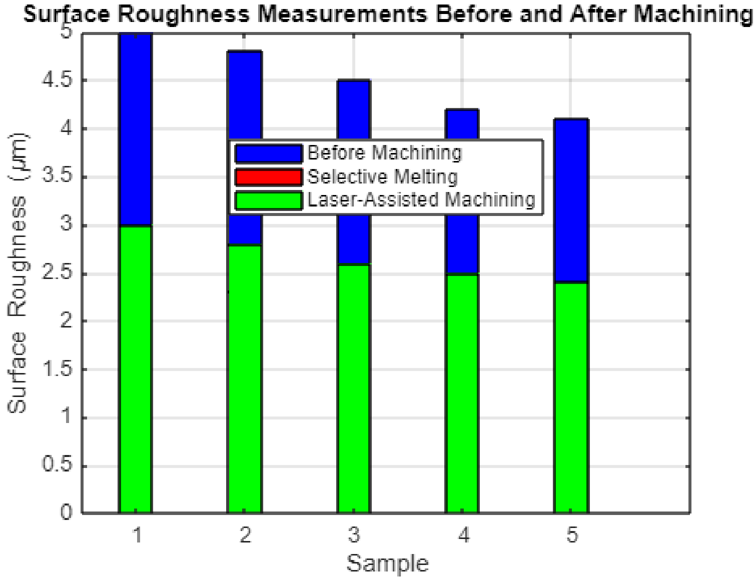

Figure. 1 Comparison of Surface Roughness Before and After Machining using Advanced Techniques

Figure. 2 illustrates the comparison of material removal rates (MRR) achieved through traditional milling and micro milling techniques. Material removal rate is a crucial parameter in machining processes, indicating the volume of material removed per unit time. Micro milling, characterized by its ability to achieve exceptionally small feature sizes and high precision, demonstrates superior material removal rates compared to traditional milling techniques. The data presented in the plot showcases the significant contribution of micro milling to machining difficult materials.

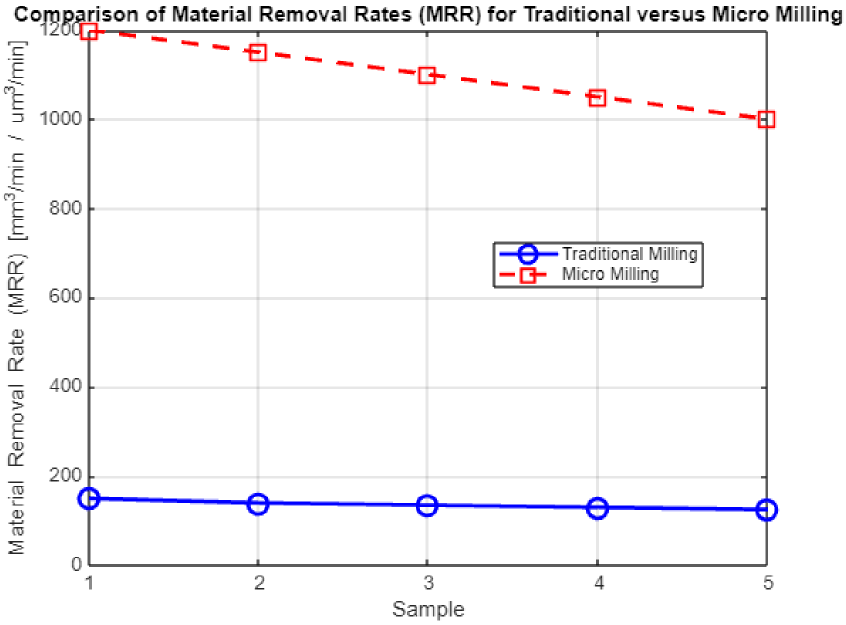

Figure. 2 Advancements in Micro Milling: Comparison of Material Removal Rates

By utilizing finer cutting tools and employing high-precision machining strategies, micro milling enhances the efficiency and effectiveness of material removal, even for challenging materials known for their hardness or brittleness. The plot suggests ample opportunities for further developments in micro milling techniques. As evidenced by the higher material removal rates achieved through micro milling compared to traditional methods, there is potential for continued refinement and optimization of micro milling processes. These advancements may include improvements in tool design, machining parameters, and process optimization, leading to even higher material removal rates and enhanced machining capabilities for difficult materials.

Figure. 3 illustrates the effectiveness of three key strategies for improving machinability: tool modifications, cooling techniques, and optimization of machining parameters. Machinability refers to the ease with which a material can be machined, taking into account factors such as tool life, machining quality, and surface integrity. Tool modifications aim to enhance tool performance and machining quality. The subplot showcases the percentage improvement in tool life and machining quality achieved through various tool modification techniques. Improved tool life results in longer tool longevity, reducing the frequency of tool changes and downtime during machining processes. Enhanced machining quality leads to smoother surface finishes, reduced surface defects, and improved dimensional accuracy of machined components.

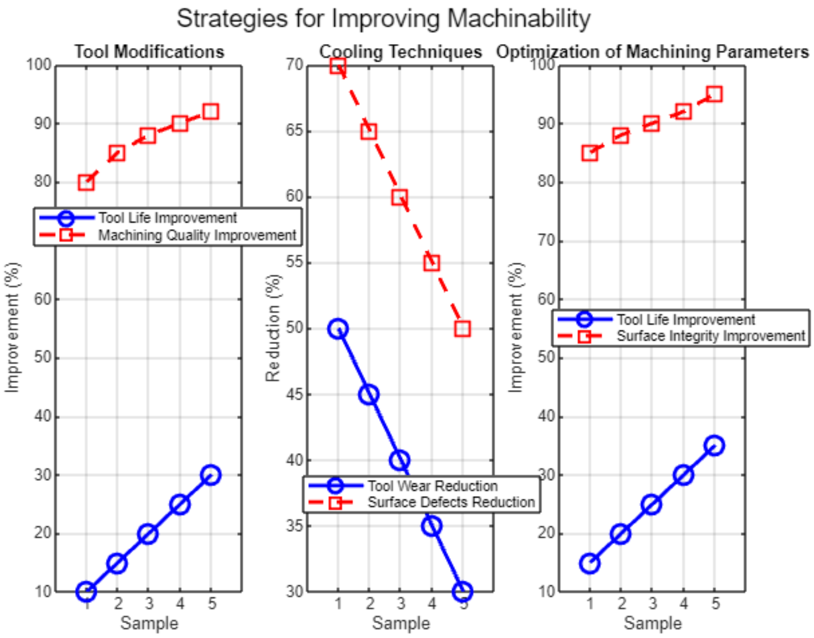

Figure. 3 Strategies for Improving Machinability

Cooling techniques play a crucial role in mitigating heat-induced tool wear and surface defects during machining. The subplot displays the percentage reduction in tool wear and surface defects achieved through different cooling techniques. Effective cooling helps maintain lower temperatures at the cutting zone, preventing excessive tool wear and thermal damage to the workpiece surface. Reduced surface defects contribute to improved surface finish and overall machining quality. Optimization of machining parameters involves fine-tuning cutting parameters to maximize tool life and surface integrity. The subplot illustrates the percentage improvement in tool life and surface integrity resulting from optimized machining parameters. By optimizing parameters such as cutting speed, feed rate, and depth of cut, machining efficiency is enhanced, leading to prolonged tool life and superior surface integrity of machined components.

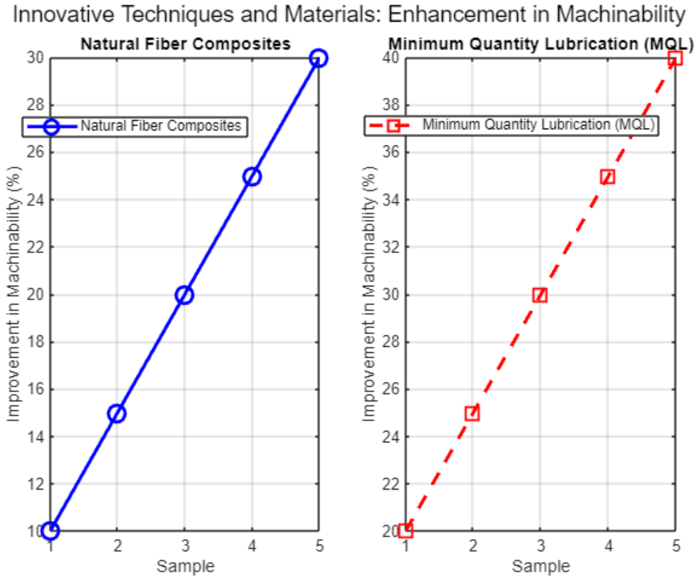

Figure. 4 Enhancement of Machinability with Innovative Techniques and Materials

Figure. 4 illustrates the effectiveness of two innovative techniques and materials, namely Natural Fiber Composites and Minimum Quantity Lubrication (MQL), in enhancing machinability. Natural fiber composites are materials derived from renewable sources such as plant fibers, which are integrated into a matrix to form a composite material. The subplot shows the percentage improvement in machinability achieved by using natural fiber composites. These composites offer advantages such as reduced tool wear, lower cutting forces, and improved surface finish during machining compared to traditional materials. The data highlights the positive impact of natural fiber composites in enhancing machinability, thereby contributing to sustainable manufacturing practices. Minimum Quantity Lubrication (MQL) is a lubrication technique that involves the application of a small amount of lubricant directly to the cutting zone during machining. The subplot displays the percentage improvement in machinability attributed to MQL. MQL improves machinability by reducing friction and heat generation at the cutting interface, leading to lower tool wear, improved chip evacuation, and enhanced surface quality. Additionally, MQL offers cost-effectiveness and sustainability benefits by minimizing lubricant usage and reducing environmental impact compared to traditional flood cooling methods.

Figure. 5 illustrates the effectiveness of Finite Element Analysis (FEA) modeling in machining processes, focusing on two key aspects: prediction of machining processes and integration of FEA in machining simulations. FEA modeling enables accurate prediction of critical parameters such as temperature distribution, chip formation, and residual stress evolution during machining processes. The subplot depicts the percentage accuracy achieved by FEA in predicting these parameters. By simulating the complex thermo-mechanical interactions occurring during machining, FEA provides valuable insights into the material behavior and process dynamics, aiding in optimizing cutting conditions and tool performance. FEA is integrated with material constitutive models and tool wear models to optimize machining processes effectively.

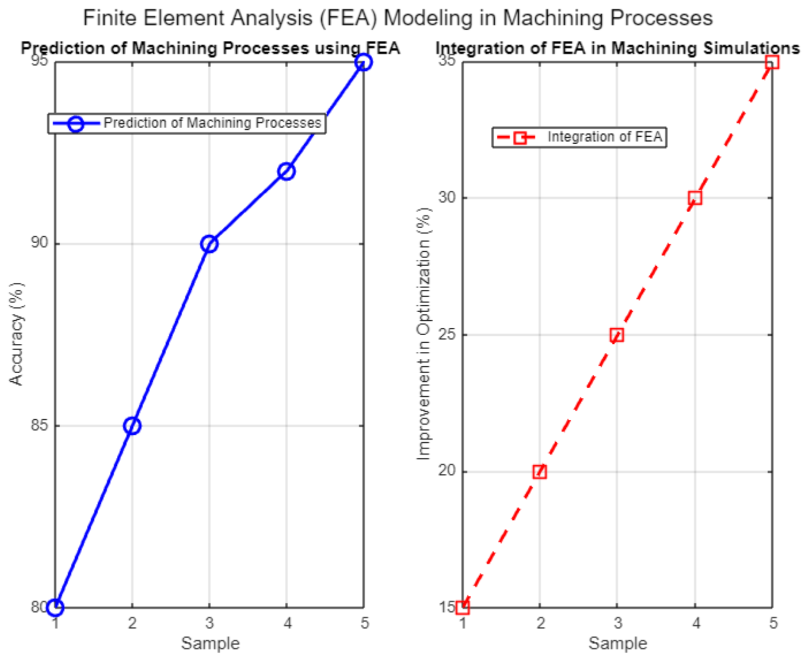

Figure. 5 FEA Modeling in Machining: Prediction and Integration

The subplot showcases the percentage improvement achieved by integrating FEA in machining simulations. By coupling FEA with material constitutive models, such as Johnson–Cook or Usui models, and tool wear models, machining simulations can accurately predict tool wear, chip morphology, and surface integrity under various cutting conditions. This integration enhances machining efficiency by providing insights into optimizing tool geometry, processing parameters, and material selection for improved performance and productivity.

RESULTS

Figure 1 illustrates a comparison of surface roughness measurements before and after machining using selective melting and laser-assisted machining techniques. The results demonstrate a significant reduction in surface roughness after machining, highlighting the effectiveness of these advanced techniques in improving surface finish and achieving smoother machined surfaces. This reduction in surface roughness underscores the potential of selective melting and laser-assisted machining for enhancing machining quality and precision. Figure 2 presents a comparison of material removal rates (MRR) achieved through traditional milling and micro milling techniques. Micro milling demonstrates superior material removal rates compared to traditional milling methods, showcasing its effectiveness in machining difficult materials. The results suggest ample opportunities for further developments in micro milling techniques, with potential enhancements in tool design, machining parameters, and process optimization. Figure 3 depicts the effectiveness of three key strategies for improving machinability: tool modifications, cooling techniques, and optimization of machining parameters. Tool modifications, such as improved tool geometry, contribute to longer tool life and enhanced machining quality. Cooling techniques play a crucial role in reducing heat-induced tool wear and surface defects, thereby improving machining efficiency. Optimization of machining parameters leads to prolonged tool life and superior surface integrity of machined components, highlighting the importance of fine-tuning cutting conditions for optimal performance. Figure 4 showcases the effectiveness of natural fiber composites and Minimum Quantity Lubrication (MQL) in enhancing machinability. Natural fiber composites offer advantages such as reduced tool wear, lower cutting forces, and improved surface finish compared to traditional materials. Similarly, MQL improves machinability by reducing friction and heat generation at the cutting interface, leading to lower tool wear and enhanced surface quality. These innovative techniques and materials contribute to sustainable manufacturing practices while enhancing machining efficiency. Figure 5 illustrates the effectiveness of Finite Element Analysis (FEA) modeling in predicting critical parameters such as temperature distribution, chip formation, and residual stress evolution during machining processes. The integration of FEA with material constitutive models and tool wear models enhances machining simulations, providing valuable insights into optimizing cutting conditions and tool performance. This integration improves machining efficiency by accurately predicting tool wear, chip morphology, and surface integrity under various cutting conditions.

DISCUSSION

The comparison of surface roughness before and after machining using selective melting and laser-assisted machining techniques demonstrates a significant reduction in surface roughness, indicating improved surface finish and smoother machined surfaces. This finding underscores the effectiveness of these advanced techniques in addressing the challenges posed by difficult-to-cut materials. The ability to achieve finer surface finishes is crucial for many engineering applications where component performance is highly dependent on surface quality. The comparison of material removal rates between traditional milling and micro milling techniques highlights the superior performance of micro milling in machining difficult materials. The higher material removal rates achieved through micro milling suggest its potential as a viable solution for improving machining efficiency and productivity, especially for applications requiring precision and small feature sizes. Further developments in micro milling techniques hold promise for enhancing material removal rates and expanding the applicability of micro milling to a wider range of materials and industries. The effectiveness of strategies such as tool modifications, cooling techniques, and optimization of machining parameters in improving machinability is evident from the presented data. These strategies contribute to longer tool life, reduced tool wear, lower surface defects, and enhanced surface integrity of machined components. By addressing factors that influence machinability, such as heat generation, tool wear, and surface finish, these strategies play a crucial role in enhancing overall machining performance and efficiency. The use of innovative techniques such as natural fiber composites and Minimum Quantity Lubrication (MQL) shows promise in enhancing machinability while promoting sustainability. Natural fiber composites offer advantages such as reduced tool wear and lower cutting forces, making them attractive alternatives to traditional materials. Similarly, MQL improves machinability by reducing friction and heat generation, leading to improved surface quality and lower environmental impact. These innovative approaches align with the growing emphasis on sustainable manufacturing practices and highlight the importance of exploring new materials and lubrication techniques to address machining challenges. The effectiveness of FEA modeling in predicting critical parameters such as temperature distribution, chip formation, and residual stress evolution during machining processes is highlighted. By integrating FEA with material constitutive models and tool wear models, machining simulations can accurately predict tool wear, chip morphology, and surface integrity under various cutting conditions. This predictive capability enables manufacturers to optimize machining processes, improve tool performance, and enhance overall machining efficiency.

CONCLUSION

The effectiveness of these advanced techniques is evident in the substantial reductions in surface roughness, improvements in material removal rates, and enhancements in tool life and surface finish achieved through strategic modifications, cooling techniques, and optimization of machining parameters. Moreover, the integration of Finite Element Analysis (FEA) modeling provides valuable insights into predicting critical parameters and optimizing machining processes, further enhancing machining efficiency and productivity. By addressing the challenges posed by difficult-to-cut materials, such as superalloys, composite materials, and ceramic matrix composites, the findings presented in the paper offer valuable guidance for manufacturers seeking to optimize machining operations and achieve superior outcomes. Embracing innovative techniques and materials not only improves machinability but also promotes sustainability and environmental responsibility, aligning with the evolving needs of modern manufacturing.

References:

1.You, K., Yan, G., Luo, X., Gilchrist, M. D., & Fang, F. (2020). Advances in laser assisted machining of hard and brittle materials. Journal of Manufacturing Processes, 58, 677-692.

2.Kishawy, H. A., & Hosseini, A. (2019). Machining difficult-to-cut materials. Mater. Form. Mach. Tribol, 10, 973-978.

3.Youssari, F. Z., Taleb, O., & Benosman, A. S. (2023). Towards understanding the behavior of fiber-reinforced concrete in aggressive environments: Acid attacks and leaching. Construction and Building Materials, 368, 130444.

4.Gholampour, A., & Ozbakkaloglu, T. (2020). A review of natural fiber composites: Properties, modification and processing techniques, characterization, applications. Journal of Materials Science, 55(3), 829-892.

5.Rusinek, R., Wiercigroch, M., & Wahi, P. (2014). Influence of tool flank forces on complex dynamics of cutting process. International Journal of Bifurcation and Chaos, 24(09), 1450115.

6.Abbas, N. M., Solomon, D. G., & Bahari, M. F. (2007). A review on current research trends in electrical discharge machining (EDM). International Journal of machine tools and Manufacture, 47(7-8), 1214-1228.

7.Zhang, Y., Xu, Z., Xing, J., & Zhu, D. (2015). Enhanced machining performance of micro holes using electrochemical discharge machining with super-high-pressure interior flushing. International Journal of electrochemical science, 10(10), 8465-8483.

8.Fontanari, V., Frendo, F., Bortolamedi, T., & Scardi, P. (2005). Comparison of the hole-drilling and X-ray diffraction methods for measuring the residual stresses in shot-peened aluminium alloys. The Journal of Strain Analysis for Engineering Design, 40(2), 199-209.

9.Bakht, M. P., Mohd, M. N. H., Shaikh, U. U., & Khan, N. (2024). Optimal Design and Performance analysis of Hybrid Renewable Energy System for Ensuring Uninterrupted Power Supply During Load Shedding. IEEE Access.

10.Zha, X., Qin, H., Yuan, Z., Xi, L., Zhang, T., & Jiang, F. (2024). Effect of cutting feed rate on machining performance and surface integrity in cutting process of Ti-6Al-4V alloy. The International Journal of Advanced Manufacturing Technology, 131(5), 2791-2809.

11.Liang, X., Liu, Z., & Wang, B. (2019). State-of-the-art of surface integrity induced by tool wear effects in machining process of titanium and nickel alloys: A review. Measurement, 132, 150-181.

12.Panagiotopoulou, O. (2009). Finite element analysis (FEA): applying an engineering method to functional morphology in anthropology and human biology. Annals of human biology, 36(5), 609-623.