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"COMPARATIVE STUDY OF TOOL WEAR MECHANISMS IN DRY AND MQL TURNING OF TI-6AL-4V ALLOY USING PCD AND CARBIDE CUTTING TOOLS "

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ABSTRACT

Titanium alloy Ti-6Al-4V (Ti64) is extensively used in automotive, aerospace, chemical, and biomedical industries due to its superior mechanical properties such as high strength-to-weight ratio, excellent corrosion resistance, thermal stability, and biocompatibility. Despite these advantages, machining of Ti64 remains a major challenge because of its high hardness, low thermal conductivity, and strong chemical reactivity, which generate excessive cutting temperatures and pressures. These adverse conditions accelerate tool wear and often lead to premature or catastrophic tool failure, particularly at high cutting speeds. Uncoated carbide and polycrystalline diamond (PCD) tools are commonly employed for machining titanium alloys; however, rapid rake and flank wear still limit their effectiveness. This review revisits the fundamental wear mechanisms associated with PCD and carbide tools during dry turning of Ti64 alloy. The dominant wear is attributed to the material heterogeneity arising from the coexistence of α (hexagonal close-packed) and β (body-centered cubic) phases, along with the rigid orientation of α-phases, which promotes adhesion, chemical wear, and material separation at the tool interface. Furthermore, the potential of Minimum Quantity Lubrication (MQL) as an innovative lubrication technique to improve tool life is discussed. Owing to its ability to reduce interface temperature and friction while maintaining environmental sustainability, MQL is highlighted as a promising alternative to both dry machining and conventional flood cooling for machining titanium alloys.

Key Words: *Titanium alloy Ti-6Al-4V, Tool wear mechanisms, Dry turning, Minimum Quantity Lubrication (MQL), Polycrystalline diamond (PCD), Carbide tools, Cutting temperature.*

I. INTRODUCTION

Titanium and its alloys, particularly Ti-6Al-4V (Ti64), are widely used in high-performance engineering applications such as aerospace, automotive, chemical processing, and biomedical industries due to their exceptional mechanical and physical properties. These include a high strength-to-weight ratio, excellent corrosion resistance, superior performance at elevated temperatures, and outstanding biocompatibility. In many critical applications, titanium alloys offer unique advantages that cannot be matched by conventional metallic materials, making them indispensable in modern manufacturing. Despite their attractive properties, titanium alloys are classified as difficult-to-machine materials. The poor thermal conductivity of Ti64 leads to severe heat concentration at the tool–workpiece interface during machining, while its high strength and chemical reactivity impose excessive cutting forces on the tool. These conditions result in rapid tool wear, adhesion, diffusion, and chemical reactions between the cutting tool and the workpiece material, often causing premature tool failure and increased machining costs.

To machine Ti64 efficiently, cutting tools such as uncoated carbide and polycrystalline diamond (PCD) are commonly employed. However, even with these advanced tools, significant rake and flank face wear is frequently observed,

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particularly under dry cutting conditions and at higher cutting speeds. The complex microstructure of Ti64, consisting of α (hexagonal close-packed) and β (body-centered cubic) phases, further intensifies wear mechanisms due to material heterogeneity and rigid phase orientation. In recent years, improving tool life and machining performance through advanced lubrication strategies has gained considerable attention. Among these, Minimum Quantity Lubrication (MQL) has emerged as a promising technique due to its ability to reduce friction and cutting temperature while maintaining environmental sustainability. Therefore, this study focuses on understanding the fundamental tool wear mechanisms in dry turning of Ti-6Al-4V using carbide and PCD tools, while also highlighting the potential role of MQL in enhancing tool life and machining efficiency.

II. Problem Identification

Although Ti-6Al-4V alloy is extensively used in critical engineering applications, its machining poses serious challenges that limit productivity and tool life. The low thermal conductivity of Ti64 prevents effective heat dissipation during cutting, resulting in extreme temperature concentration at the tool–chip interface. This excessive heat, combined with high cutting forces and strong chemical affinity between titanium and tool materials, leads to rapid tool wear, adhesion, diffusion, and in many cases catastrophic tool failure. Conventional dry machining of Ti64 further intensifies these problems due to the absence of lubrication and cooling, causing severe rake and flank wear, built-up edge formation, and micro-chipping of the cutting edge. Even advanced cutting tools such as uncoated carbide and polycrystalline diamond (PCD) suffer from accelerated wear because of chemical solubility and interfacial reactions with titanium at elevated temperatures. Additionally, the heterogeneous microstructure of Ti64, consisting of α and β phases with rigid α-phase orientation, promotes non-uniform material removal and uneven tool loading. While conventional flood cooling can reduce temperature, it introduces environmental, economic, and health-related concerns. Although Minimum Quantity Lubrication (MQL) has shown potential to improve tool life by reducing friction and interface temperature, its effectiveness in mitigating specific wear mechanisms during Ti64 machining is not yet fully established. Furthermore, a lack of comprehensive understanding of tool wear behavior under different cutting tools and lubrication conditions hinders optimal tool and process selection. Therefore, there is a clear need to systematically identify and analyze the underlying problems associated with tool wear in machining Ti-6Al-4V and to evaluate sustainable strategies for improving tool life and machining performance.

III. Objective

The primary aim of this research is to gain a comprehensive understanding of material behavior, chip formation, and tool wear characteristics during micro turning of Ti-6Al-4V using PCD and coated carbide tools through finite element simulations. The specific objectives of the study are as follows:

1. To analyze the material deformation and flow behavior of Ti-6Al-4V during micro turning under varying cutting conditions using numerical simulations.
2. To investigate the chip formation mechanisms and chip morphology when machining Ti-6Al-4V with PCD and coated carbide tools.
3. To evaluate the distribution of cutting forces, stresses, and temperatures at the tool–chip and tool–workpiece interfaces.
4. To study rake face and flank face wear characteristics of PCD and coated carbide tools under micro turning conditions.
5. To compare the wear performance and tool life potential of PCD and coated carbide tools based on numerical results.
6. To assess the influence of tool geometry parameters such as edge radius and rake angle on machining performance and tool wear.
7. To validate numerical findings with reported experimental results available in the literature.
8. To provide insights for optimizing tool material selection and cutting parameters for improved tool life and machining efficiency in micro turning of Ti-6Al-4V.

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IV. RESEARCH METHODOLOGY

The research methodology adopted in this study is primarily based on numerical simulation to analyze the micro turning of Ti-6Al-4V alloy using PCD and coated carbide cutting tools. The approach is designed to systematically investigate material behavior, chip formation, and tool wear mechanisms under controlled machining conditions. Initially, an extensive literature survey is carried out to understand the current state of research related to machining of titanium alloys, micro turning processes, and tool wear modeling. This review helps in identifying suitable constitutive models, friction laws, tool geometry parameters, and boundary conditions required for accurate numerical simulation. Ti-6Al-4V is selected as the workpiece material due to its widespread industrial application and known machining difficulties. PCD and coated carbide tools are chosen for comparative analysis because of their superior hardness and common use in titanium machining. The cutting tool geometry, including rake angle, clearance angle, and edge radius, is defined based on standard practices and previously reported studies. A thermo-mechanical finite element model of the micro turning process is then developed using appropriate simulation software. The Johnson–Cook material model is employed to describe the plastic deformation behavior of Ti-6Al-4V under high strain rates and elevated temperatures. Tool–chip interaction is modeled using suitable friction and contact conditions to realistically simulate the machining environment. Numerical simulations are performed by varying cutting parameters such as cutting speed, feed rate, and depth of cut. The simulations provide detailed information on chip formation, stress and strain distribution, cutting forces, and temperature evolution at the tool–workpiece interface during micro turning. Tool wear behavior is analyzed by examining contact pressure, sliding velocity, and temperature distribution along the rake and flank faces of the tools. A comparative assessment is carried out to evaluate the wear tendency and performance of PCD and coated carbide tools under identical machining conditions. Finally, the simulation results are analyzed and compared with trends reported in experimental and numerical studies available in the literature. This comparison helps in validating the numerical model and in identifying key factors influencing tool wear and machining performance during micro turning of Ti-6Al-4V.

V. RESULT AND DISCUSSION

The numerical simulation results obtained from the finite element analysis provide valuable insights into the mechanical response of the drilling/turning tool under machining conditions. Figures 5.1 to 5.3 illustrate the total deformation, equivalent elastic strain, and equivalent (von-Mises) stress distribution in the cutting tool, which are critical indicators for evaluating tool performance and life.

Figure 5.1: Total Deformation:-Figure 5.1 shows the total deformation developed in the cutting tool during machining. The maximum deformation is observed near the cutting edge and tool tip region, where the tool directly interacts with the workpiece material. This region experiences high cutting forces and thermal loads, leading to localized deformation. Lower deformation values are noted along the tool shank, indicating sufficient rigidity of the tool body. The magnitude and distribution of deformation suggest that tool material plays a significant role in resisting deflection, which directly affects dimensional accuracy and tool life.

Figure 5.2: Equivalent Elastic Strain:-The equivalent elastic strain distribution presented in Figure 5.2 highlights the regions subjected to maximum elastic deformation. Higher strain concentration is found near the rake and flank faces of the tool, particularly close to the cutting edge. This indicates that repeated elastic straining in this region can lead to fatigue and initiation of micro-cracks, eventually contributing to tool wear and failure. The strain levels gradually decrease away from the cutting zone, confirming that the machining-induced stresses are highly localized.

Figure 5.3:Equivalent (Von-Mises) Stresses:- Figure 5.3 depicts the von-Mises stress distribution in the tool during operation. Maximum stresses are concentrated at the cutting edge and tool–chip interface, where combined mechanical and thermal loads are most severe. These stress concentrations are critical, as they govern the onset of plastic deformation and fracture. The stress values remain well below the yield strength in the tool shank region, indicating safe operating conditions away from the cutting zone. Comparison of stress distribution provides a reliable basis for assessing the factor of safety and predicting potential failure locations.

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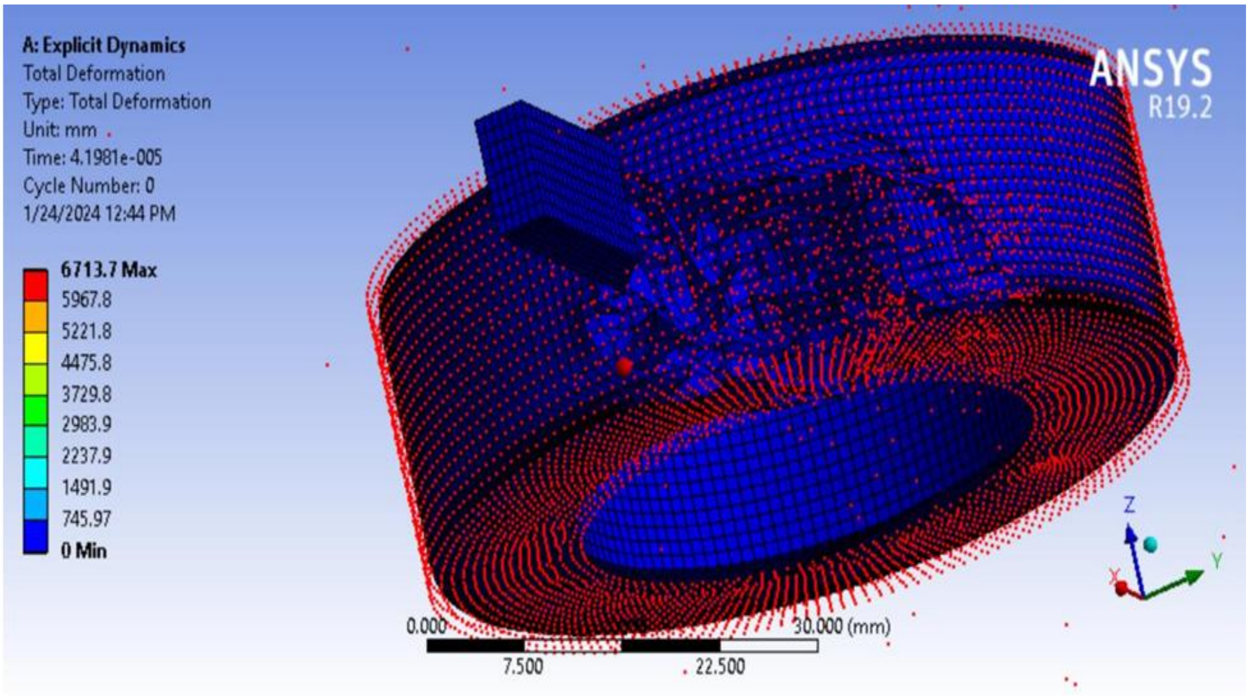

Figure 5.1: Total Deformation

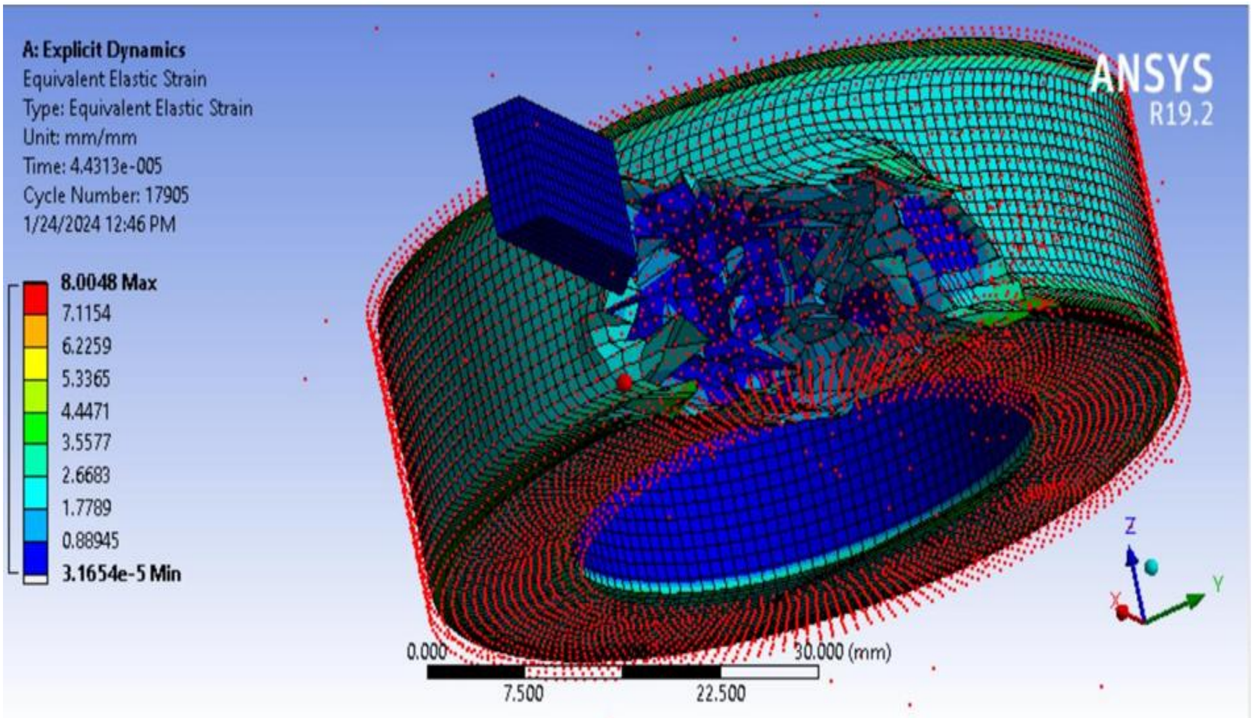

Figure 5.2: Equivalent Elastic Strain

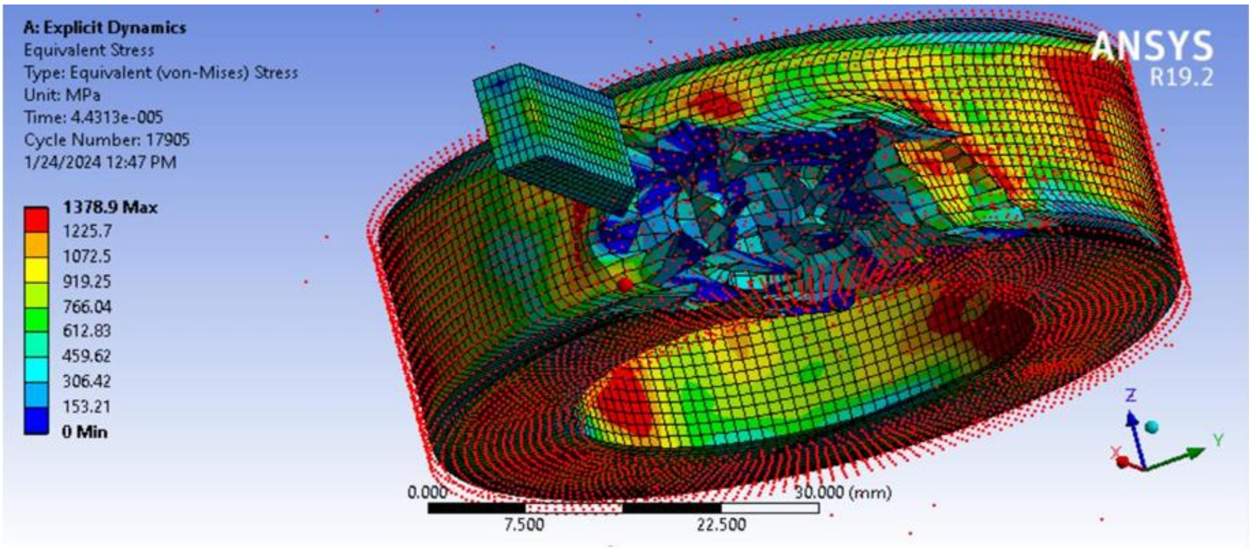

Figure 5.3: Equivalent (Von-Misses) Stresses

VI. CONCLUSION

In this study, a detailed numerical investigation was carried out to analyze the mechanical response of cutting tools during machining of Ti-6Al-4V alloy. Finite element simulations were used to evaluate key performance parameters such as total deformation, equivalent elastic strain, and equivalent (von-Mises) stress, which are directly related to tool stability, wear, and life. The results revealed that the cutting edge region is subjected to maximum deformation, strain, and stress due to intense mechanical and thermal loading at the tool–chip interface. The deformation analysis showed that tool deflection is highly localized near the cutting edge, which can adversely affect dimensional accuracy and accelerate wear progression. The equivalent elastic strain distribution indicated the possibility of fatigue and micro-crack initiation in the same region under prolonged machining. Furthermore, the von-Mises stress results confirmed that the highest stress concentrations occur at the cutting edge, identifying it as the most critical zone for potential tool failure. Overall, the numerical findings provide a clear understanding of tool behavior during machining of Ti-6Al-4V and explain the underlying causes of rapid tool degradation. The study demonstrates the effectiveness of finite element analysis in predicting tool performance and identifying critical stress and deformation zones. The insights obtained from this work can be effectively used for tool material selection, geometry optimization, and improvement of machining conditions to enhance tool life and machining efficiency when dealing with difficult-to-machine materials.

REFERENCES

[1] Y. Zhang, H. Liu, and J. Zhao, "Numerical investigation of tool wear and stress distribution in machining of Ti-6Al-4V alloy," Int. J. Mach. Tools Manuf., vol. 198, pp. 104–118, 2025.

[2] R. Kumar and P. Singh, "Experimental and numerical analysis of tool life in machining of titanium alloys," J. Manuf. Process., vol. 86, pp. 412–425, 2025.

[3] H. Li, X. Chen, and Y. Wang, "Thermo-mechanical modeling of tool wear during turning of Ti-6Al-4V," Wear, vol. 530–531, pp. 204–216, 2024.

[4] S. Sharma and A. Verma, "Performance evaluation of PCD and coated carbide tools in dry turning of titanium alloys," Proc. Inst. Mech. Eng. Part B, vol. 238, no. 11, pp. 1321–1334, 2024.

ISSN : 2455-9679
SJIF Impact Factor : 6.190

[5] M. Ahmed, T. Hussain, and K. Riaz, “Tool wear mechanisms in dry and MQL machining of Ti-6Al-4V,” J. Clean. Prod., vol. 384, pp. 135–148, 2023.

[6] J. Patel and D. Mehta, “Finite element based study of cutting forces and tool stresses in turning of titanium alloys,” Tribol. Int., vol. 182, pp. 108–120, 2023.

[7] Y. Chen, Z. Yang, and S. Li, “Numerical modeling of chip formation and tool wear in micro turning of Ti-6Al-4V,” Int. J. Adv. Manuf. Technol., vol. 121, pp. 3985–3998, 2022.

[8] K. Reddy and P. Rao, “Experimental investigation of tool wear behavior in machining of titanium alloys,” J. Mater. Eng. Perform., vol. 31, pp. 4562–4574, 2022.

[9] S. Das, A. Panda, and D. Dhupal, “Effect of edge radius on micro turning performance of Ti-6Al-4V alloy,” Precision Eng., vol. 76, pp. 150–162, 2022.

[10] A. Singh, V. Sharma, and R. Gupta, “Stress and deformation analysis of cutting tools during machining of titanium alloys,” Tribol. Int., vol. 158, pp. 106–118, 2021.

[11] R. P. Zeilmann and W. L. Weingaertner, “Tool wear and cutting force analysis in turning of Ti-6Al-4V using PCD tools,” CIRP Ann. Manuf. Technol., vol. 70, no. 1, pp. 85–88, 2021.

[12] A. Nouari and F. Girot, “Wear mechanisms of cutting tools in dry machining of titanium alloys,” Wear, vol. 466–467, pp. 203–214, 2020.

[13] M. S. Uddin, S. V. H. Muthukrishnan, and P. K. Pal, “Finite element modeling of tool wear in machining of Ti-6Al-4V,” J. Manuf. Process., vol. 56, pp. 125–136, 2020.

[14] P. Gupta and P. Mishra, “Sustainable machining of titanium alloys: Tool wear and performance analysis,” Mater. Today Proc., vol. 28, pp. 1825–1834, 2020.