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Evaluating the Efficiency of Micro End Mill Tools and Performance Metrics in Micro Milling

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Abstract

Recent improvements in micro-milling, tool treatments, and ultra-precision machining centres have made it easier to produce tiny, high-quality parts for various industries. This paper looks at the latest developments in these areas, focusing on how new tools, surface treatments, and advanced machining technologies have helped improve accuracy, surface finish, and the lifespan of tools. These advancements have made a big impact in industries like biomedical engineering, electronics, and aerospace. The paper also talks about future research, emphasising the need for continued innovation to keep up with the growing demand for precise micro-manufacturing. The study deals with the study of micro tools, coatings and cryogenic treatment and their effect on machining outcomes. The paper discusses the importance of coating and cryogenic treatment on micro end mill tools so as to reduce friction and enhance tool life for better productivity and surface quality of the machined surface. The study provides a discussion on the utilisation of different tools, their performances, major changes, and impact on machining. Cryogenic treatments are observed to show key benefits during machining of all kinds of surfaces, their ability to reorient, reduction of overall grain size and resistance to wear allow it to last long during machining.

Major Findings: *Deep Cryogenic Treatment (DCT), especially DCT-24, significantly improves tool performance by enhancing microstructure, hardness, and wear resistance, while coated tools like TiAlN, TiSiN, and DLC coatings further extend tool life and surface quality by reducing friction and burr formation. Proper optimisation of machining parameters (spindle speed, feed, and depth of cut), along with advanced strategies like MQL, cryogenic cooling, and machine learning-based tool wear monitoring, plays a crucial role in minimising wear and enhancing machining efficiency. Cryogenically treated tools, particularly in aluminium alloy machining, show the best durability and cost-effectiveness, outperforming both untreated and coated tools over longer operations.*

Keywords: *Micro-Manufacturing, Micro Milling, Tool Treatments, Ultra-Precision Machining, Surface Finish*

1.0 Introduction

Micro-milling is a highly precise machining process that has gained significant attention in industries requiring exceptional accuracy and fine surface finishes. Micro-milling involves tools with diameters typically smaller than 1 mm, capable of producing intricate micro-geometries and fine finishes on parts. This technology is especially valuable in sectors such as aerospace, medical devices, and microelectronics, where the demand for high-precision components is paramount. What makes micro-milling particularly unique is its ability to create microfeatures—smaller than 1 mm—on workpieces of various sizes. Micro-milling stands out when compared

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to other precision techniques like micro-turning or Electrical Discharge Machining (EDM) as it has better material removal rates and gives a good finish. The ability to manufacture small parts with precise dimensional accuracy and a fine surface texture has made it indispensable in industries with stringent requirements for both functionality and aesthetics, such as the medical and aerospace sectors. Advancement of ultra-precision, high-speed machining centres has further enhanced the capabilities of micro-milling, making it a leading process in the realm of micro-manufacturing.

The performance and efficiency of micro-milling are heavily influenced by the choice of cutting tool materials. Tungsten carbide (WC) is widely used due to its hardness and ability to retain a sharp cutting edge. These properties make it particularly suitable for handling the stresses and challenges of micro-milling, where the tool is subjected to rapid wear. Additionally, tungsten carbide's high thermal stability ensures that the cutting edges remain intact even at elevated temperatures, extending tool life and maintaining consistent performance over long machining periods. However, despite its durability, tungsten carbide tools still experience wear when machining difficult materials like aluminium alloys. To address this, advancements such as cryogenic treatments and specialised coatings have been developed, which significantly improve the longevity and performance of tungsten carbide tools in micro-milling applications. At higher rotational speed, when the tool machines the surface of the workpiece material the high heat is generated due to friction between the tool and the workpiece, due to shear zone heat due to material removal. Different issues can be associated with different materials, like BUE (Build Up Edge) in case of Aluminium Alloys, where workpiece material gets adhesion at the tool edge that leads to uneven wear and higher forces, to get rid of this different coatings, and cryogenic treatment can be done to reduce the issue associated.

2.0 Literature Survey

Shingea and Dabadeb[1]: An experiment was conducted on AA 6063 T6 using a 2-fluted tungsten carbide tool with a diameter of 400 µ to evaluate the Material Removal Rate (MRR) and machining parameters on machining performance. The machining was performed in a low-speed range with SS values of 1,000, 1,500, 2,000, and 2,500 rpm, Feed Rates (FR) values of 1.8, 2.7, 3.6, and 4.5 mm/min, and DOC (Depth of Cut) values of 0.16, 0.32, 0.48, and 0.64 mm. The MRR was calculated using the product of Depth of cut and FR. The experiment followed an L16 orthogonal array with 4 levels and 3 factors under dry conditions. Results showed that as the FR and DOC increase, the MRR increases, with a slight upward trend in MRR also observed as spindle speed increased. However, it was found that higher FR and DOC, along with increased spindle speeds, could lead to a loss of tool stability, causing dimensional changes and resulting in an increase in the width of the cut. This highlights the need to balance machining parameters to maintain stability and optimise MRR while minimising dimensional variations during the machining of AA 6063 T6.

Varghese *et al.*[2]: The experiment on Inconel material using a 760-micron diameter uncoated and Diamond like coated tool, with coating done using Plasma Enhanced Chemical Vapour Deposition (PECVD), aimed to evaluate tool wear and performance. The uncoated and DLC-coated tools were subjected to cutting at various feed rates (1.25 to 5 µ per flute) and depths of cut (0.1 to 0.3 µ) at a SS of 20,000 RPM. Coating thickness increased the tool's cutting edge diameter from 2 to 3 µ and improved hardness from 1680 to 2500 HV 0.05, leading to a reduction in the coefficient of friction (0.1 - 0.2). Tool failure primarily occurred due to flank wear, Built-Up Edge (BUE), and chipping, which resulted in a reduction in tool diameter and cutting edge radius. The study highlighted that low feed rates can lead to insufficient chip formation, causing ploughing, which increases stress and tool wear. In contrast, the DLC coating, being a solid lubricating type with low adhesion properties, reduced BUE and friction, thus improving tool life and machining quality. The DLC-coated tool showed reduced wear, especially in flank wear and chipping, and minimised tool diameter loss. Additionally, the DLC coating improved the quality of the surface of the machined material by reducing BUE and positively affecting surface roughness. It also lowered cutting forces due to its low friction properties and exhibited better performance over longer cutting distances, resulting in less burr formation compared to the uncoated tool.

Baig *et al.*[3]: An experiment was conducted on Monel 400 using various tool coatings (TiAlN, TiSiN, nACo,

and an uncoated tool) to investigate the effects on surface finish, burr height, and width in high-speed machining. The study involved a 500-micron, 2-fluted micro tool in dry conditions, with four parameters Depth of Cut (DOC) of 35, 65, 95, and 125 µ, feed rate of 0.5, 1, 2, and 4 µ/tooth, and cutting speeds of 50, 75, 100, and 125 m/min). Results indicated that selecting a feed rate just above the cutting edge radius achieved the best surface finish. Among the coatings, TiSiN-coated tools achieved the minimum Ra value, attributed to their higher coefficient of friction, which increased the temperature in the cutting zone, facilitating easier material removal. Conversely, nACo-coated tools, which have the highest hardness, resulted in higher Ra values due to increased cutting forces. Feed rate was found to be the most influential factor affecting both Ra and burr formation (height and width) during both up and down milling operations. Coated tools outperformed uncoated tools in terms of surface finish and burr control, highlighting the importance of selecting the right coating and optimising feed rate for improved machining performance on Monel 400.

Muhammad *et al.*[4]: An experiment was conducted on Inconel 718 to investigate the effects of different tool coatings (AlTiN, nACo, and TiSiN) on surface roughness (Ra), tool wear, and burr width and height during up and down milling operations. The experiment utilised a 2-fluted, 500 µ tool in a dry machining environment, with cutting Speeds (SS) of 8, 10, and 12 m/min, feed of 0.2, 0.6, and 1 µ, and DOC of 3, 60, and 90 µ. The study focused on how these parameters affected the machining performance of coated tools. TiSiN-coated tools exhibited the best Ra values, attributed to their high coefficient of friction, which was beneficial for the cutting length of 10 mm. In contrast, tools coated with nACo experienced more significant BUE formation, leading to higher Ra values, as the coating was harder than the other two. AlTiN-coated tools produced less top burr formation compared to TiSiN-coated tools, which showed longer burrs due to the higher cutting edge resulting in more cutting forces. The DOC was identified as the most important factor.

Influencing burr formation, while cutting velocity was the primary factor affecting surface roughness.. Both Ra and top burr formation were most influenced by cutting velocity, and the coefficient of friction of the tool coating played a crucial role in either increasing or decreasing surface roughness and burr formation. These results highlight the importance of selecting appropriate tool coatings and optimising cutting parameters to improve surface quality and reduce tool wear and burr formation in Inconel 718 machining.

Davoodi *et al.*[5]: An experiment was conducted on N-155, an iron-nickel-based superalloy, using a Physical Vapour Deposited TiAlN-coated cemented tools of 200-micron diameter in a lathe-based low-speed micro-machining process. The machining parameters included cutting speeds up to 90 m/min and feed rates up to 0.200 mm/rev under dry conditions. The study focused on understanding the effect of speed and FR on the tool life during the machining of this challenging material. The results indicated that both cutting speed and feed rate, along with the product of cutting speed and feed rate, had a significant impact on tool life. Higher cutting speeds and feed rates accelerated tool wear, shortening the tool's effective life. The product of speed and FR was particularly influential, highlighting the importance of optimising these parameters to enhance tool life and maintain machining efficiency. This study emphasises the critical role of cutting conditions in prolonging the durability of tools used for machining high-performance alloys like N-155.

Zariatin[6]. An experiment was conducted on Aluminium Alloy 1100 for the manufacturing of a micro impeller, utilising various upmilling strategies such as Zig, Follow Contour, and Follow Profile. Tool runout measurement is done to get the actual diameter of the tool and evaluate its impact on machining accuracy. The machining parameters included spindle speeds (SS) of 70,000 rpm with a feed rate of 30 mm/min, and 95,000 rpm with a feed rate of 60 mm/min, using a 2-fluted, 2mm diameter coated with TiAlN tool in dry machining. The study emphasised the importance of understanding tool runout, as it directly affects the precision of the manufacturing process. The minimum thickness observed during machining was 11.7 µm, but due to tool runout deviations, the effective thickness was considered to be 15 µm. The target thickness requirement was 3 µm, highlighting the significant impact of tool runout on achieving the desired micro-level accuracy in micro-impeller manufacturing.

Vázquez *et al.*[7]: An experiment was conducted on stainless steel (316L) and titanium (Ti6Al4V), materials commonly used in the manufacturing of medical devices such as catheters, stents, and aneurysm clips. The study utilised a 2-fluted, 200-micron diameter Aluminium Titanium Nitride (AlTiN)-coated tool to machine micro-channels under both dry and coolant-based conditions. The machining parameters included SS up to 12,000 rpm, depths of cut (DOC) of 20 and 50 µ, and FR 1.25 mm/min, with channel depths of 50 and 100 µ. The coolant used was oil-based, and the materials had hardness values of 88 HRB for stainless steel (316L) and 107 HRB (32 HRC) for titanium (Ti_6Al_4V). The results indicated that wet conditions give a better geometric shape than compared to dry conditions, with the channels being more rounded in dry conditions for stainless steel and rectangular for titanium. In terms of Ra, the wet condition provided the best results for stainless steel, while for titanium, both wet and low-speed conditions showed the best Ra values. For stainless steel, higher FR and coolant use produced a more stable machining process, achieving depths close to 200 µ and allowing proper depth in dry conditions, with higher speeds contributing to better depth control. In contrast, for titanium, higher feed rates combined with dry conditions resulted in a more stable process. This study demonstrates that both the material being machined and the cooling conditions significantly influence the stability of the machining process, the good roughness value, and the achievable depth in medical-grade materials.

Zhang *et al.*[8]: An experiment was conducted on carbide tools with different Cobalt (Co) percentages (12%, 20%, 40% and 80%) to study the effects of Differential Carbide Treatment (DCT) using SEM and XRD. Cobalt exists in two crystal structures: the face-centred cubic (α-Co) and the hexagonal close-packed (ε-Co) phases. Below 417°C, the hexagonal phase (ε-Co) has higher hardness, strength, and wear resistance compared to the α-Co phase, which is more stable. The study found that in WC–12Co and WC–20Co cemented carbides, the cobalt diffraction peaks were weak, making it difficult to detect changes in the cobalt crystal structure after DCT. However, in WC–40Co, the diffraction peaks were clearer, and an increase in the ε-Co phase is observed after DCT, although the changes were subtle. In WC–80Co, the cobalt diffraction peaks were more prominent, allowing for clearer observation of the effects of DCT. After DCT, the ε-Co peaks slightly strengthened, but there was no major change. The results suggest that DCT treatment slightly increases the ε-Co phase in WC-Co cemented carbides, especially in higher cobalt compositions like WC–80Co. This increase in the harder ε-Co phase enhances the overall hardness of the material, but the effect is most noticeable in the WC–80Co composition, where the changes were more distinct.

Ucun *et al.*[9]: The experiment aimed to investigate tool wear in titanium alloy by comparing the performance of different coated tools: uncoated, AlCrN-based, AlTiN-based, and TiN-coated cemented carbide tools (500µ, 9% cobalt). The tools were tested under high-speed machining conditions with a cutting speed of 20 m/min, a FR of 2 µ, and a depth of cut (DOC) of 50 µ over a cutting length of 640 mm. The cutting edge radii for the uncoated, AlCrN-based, AlTiN-based, and TiN-coated tools were 0.41, 0.9, 1.2, and 1.5 µ, respectively. During machining of the Ti-6Al-4V workpiece, a built-up layer formed on the flank face of the micro end mills, causing abrasive wear on the uncoated tool, which led to cutting edge breakage and rounding. In comparison, the AlTiN-coated tool showed better wear resistance, keeping its cutting edge more intact with less rounding. As the cutting length increased, the uncoated tool experienced rapid flank wear, while the AlCrN-based and TiN-coated tools wore less, with the AlTiN-coated tool performing the best. Additionally, the AlTiN-coated micro end mill provided the best Ra values, making it the most effective coating for this application.

Ucun *et al.*[10]: An experiment was conducted on Inconel 718 using a 2-fluted 760-micron tungsten carbide tool, comparing the effects of uncoated, cryo treated, and in MQL conditions on tool wear, surface quality (Ra) and burr formation. The machining parameters included a speed of 48 m/min, feed rates of 1.25, 2.5, 3.75, and 5 mm/flute, and depths of cut of 0.2 mm. Cryogenic pre-cooling reduces the cutting zone temperature, leading to a decrease in burr formation and Ra compared to untreated conditions. The MQL condition, using Coolube 2210 lubricant, prevents the formation of BUE by maintaining a stable cutting temperature, but it does not directly reduce burr formation. Ra values were lower in cryogenic pre-cooling conditions, and they were similar to those in MQL. The MQL condition contributed to reduced tool wear, indirectly helping to decrease burr

formation. In both untreated and cryogenic cooling scenarios, the increase in local contact area temperature led to adhesion and BUE effects, especially due to the CrN phase in the AlCrN coating. However, these issues were minimised under MQL conditions. Cryogenic cooling also led to a reduction in tool diameter, as the tool edge radius increased due to wear, resulting in burr formation. Overall, cryogenic pre-cooling yielded better results in terms of surface quality and tool longevity.

Clara *et al.*[11]: The effect of coated and uncoated tools with a 1mm diameter on the machining of titanium alloys, specifically focusing on surface quality, has been studied using two-fluted tools. The tools, both uncoated and coated with SIRON-A, were tested at varying feed rates of 1, 8, and 15 µm/flute, with an SS of 44,600 rpm and a DOC of 0.2 mm in dry machining. Surface roughness measurements, including the Sa and Ra values, were used to assess the quality of the surface. The Sa value was observed to remain constant in the middle of each slot, while the Ra value showed a dependence on the feed rate. Fast Fourier Transform (FFT) analysis revealed that the feed marks on the machined surface were precisely double the values of the feed/tooth, with the feed marks, feed per rotation. The vibration at this frequency was identified as a key factor contributing to the feed marks observed on the surface. This study highlights the influence of feed rate, tool coating, and system vibrations on the surface finish when machining titanium alloys with small-diameter tools.

Mokhtar *et al.*[12,13]: An experiment was conducted on AA 6061 T6 using micro tools for the fabrication of micro channels in fluidic devices, employing Central Composite Design (CCD) for statistical optimisation. The experiment used 2-fluted TiAlN-coated micro tools with a diameter of 200 µ, operating in a low-speed range under dry machining conditions. The Spindle Speeds (SS) tested up to 20,000 rpm, with feed rates up to 300 mm/min, and DOC of 50, 125 and 200 µ. The results revealed that an increase in Spindle Speed (SS) led to higher cutting velocity across the tool rake face, resulting in increased tool wear, which caused plowing action and the formation of burrs. With an increase in SS and DOC, surface roughness (Ra) decreased, while a decrease in feed increases Roughness, showing a linear relationship. The DOC contributes to burr formation. As SS and DOC increased, the burr width also increased, while a decrease in feed rate reduced burr width. The results indicated that higher cutting velocities and longer machining times raised the likelihood of tool wear, which in turn resulted in rougher surface finishes. Therefore, the study emphasises the need for careful optimization of SS, feed rate, and DOC to minimise tool wear and burr formation while achieving desired surface quality in micro machining for fluidic device applications.

Bhople *et al.*[14]: Cryogenic treatment, specifically Deep Cryogenic Treatment (DCT), has been shown to significantly enhance the performance of WC-Co end mill cutters used for machining Ti-6Al-4V. Tools in cryogenic temperatures of -100°C and -180°C for varying durations (8, 16, and 24 hours), followed by tempering at 150°C for 2 h, displayed notable improvements in microstructure. DCT-24 tools exhibited the strongest bonding between cobalt (Co) and Tungsten carbide (WC), accompanied by a reduction in grain size to 563.6 nm, compared to untreated tools, which maintained a grain size of 1004.45 nm. SEM and EDS analysis revealed the formation of η carbide (Co_3W_3C or Co_6W_6C) phases during cryogenic treatment, which contributed to the enhancement of the tool's structural integrity. The Vickers microhardness test indicated a 9% increase in hardness for DCT-treated tools, reflecting improved resistance to wear. The cutting force measurements revealed that DCT-24 tools exhibited lower cutting forces, a result of improved thermal conductivity and minimised build-up edge (BUE) formation. Conversely, tools subjected to Sub-zero Cryogenic Treatment (SCT), particularly SCT-8, were more susceptible to abrasion and BUE formation due to lower thermal conductivity. DCT-24 tools demonstrated enhanced wear resistance and extended tool life due to reduced BUE formation and improved thermal management. While the cryogenic treatment duration of 24 h appeared to offer optimal results, further investigation into longer treatment times, as well as the application of coatings on cryogenically treated tools, could further enhance tool durability, cutting efficiency, and overall performance in machining applications.

Özbek[15]: An experiment on AISI 11 steel using cryo-treated tools aimed to study the microstructure and microhardness of tools coated with TiCN/Al_2O_3/TiN and made of tungsten carbide. The tools underwent Sub-zero Cryogenic Treatment (SCT) for 6 hours at -80°C and -196°C, and Deep Cryogenic Treatment (DCT) for

24 hours at -197°C, all in dry machining conditions. Energy Dispersive Spectroscopy (EDS) analysis revealed angularly shaped grains and the presence of white veins, with the phase composition showing 59.76% tungsten (W), 34.87% cobalt (Co), and 4.22% carbon (C). The cobalt-bonded carbides exhibited two eta phases: $(Co_3W_3)C$ and $(Co_6W_6)C$. The hardness measurements indicated the highest increase of 10.87% for DCT-24 tools, while DCT-6 and SCT-6 tools showed hardness increases of 8.8% and 3.4%, respectively. Cryo-treated tools demonstrated less wear compared to untreated tools (UT), indicating improved hardness and wear resistance. Notably, SCT-6 outperformed both DCT-6 and UT tools in terms of wear resistance. Additionally, surface roughness (Ra) measurements revealed that cryo-treated tools provided better Ra values than untreated tools, with flank wear being influenced by cutting speed, while Ra was more sensitive to feed rate. This experiment highlights the enhanced durability and surface quality achieved through cryogenic treatment, with DCT-24 providing the most significant improvements in tool performance.

He *et al.*[16]: An experiment was conducted on additively manufactured aluminium alloys, AlSi7Mg and AlSi10Mg, to evaluate their performance during micro milling operations using a 2-fluted, 100-micron diameter cemented carbide tool. The machining was performed in a low-speed range with spindle speeds (SS) of 9,554, 14,331, 19,108, and 23,885 rpm, FR of 1, 2, 3, and 4 µm/tooth, and depths of cut (DOC) of 20, 30, 40, and 50 µ, under dry conditions. The alloys were produced using Selective Laser Melting (SLM), with AlSi7Mg exhibiting a hardness of 110.5, and AlSi10Mg a hardness of 120.7. During the process, the silicon Si tends to oxidise, to form hard SiO2 particles that can detach during cutting, negatively impacting surface finish. Results showed that as spindle speed (SS) increased, cutting forces also increased, with the AlSi10Mg alloy showing higher cutting forces compared to AlSi7Mg. Specifically, the Fy and Fz force components, and component Fx for AlSi10Mg were 21.9%, 10.4%, and 30.7% higher, respectively, than for AlSi7Mg. Additionally, surface roughness (Ra) decreased with higher spindle speeds and increased with lower feed rates. AlSi10Mg exhibited 26.9% higher surface roughness than AlSi7Mg, primarily due to its higher Si content, which resulted in increased cutting forces. This study demonstrates the influence of alloy composition and micro milling operations, highlighting the trade-offs between cutting forces, surface finish, and alloy hardness.

Kundiya *et al.*[17]: An experiment was conducted on titanium to analyse the effects of various machining parameters on the quantity of holes drilled. The experimental design was based on an with spindle speeds ranging from 25,000 to 45,000 rpm, and drill sizes up to 400 µm. The machining was performed using 2-fluted TiN-coated tools with diameters ranging from 0.2 to 0.5 µm in a dry machining environment. Acoustic emission (AE) analysis revealed that the highest RMS values were obtained during high-speed micro drill operation with a moderate tool diameter, with higher feed rates leading to increased AE RMS due to higher frictional forces and tool wear. The Amplitude Signal Level (ASL) showed lower acoustic emissions at higher speeds, and larger tool diameters resulted in longer cutting edges, leading to more material removal per pass, which in turn produced higher ASL values. The tool diameter was found to significantly affect the number of holes drilled before the tool failed. Specifically, as the feed rate and tool size increased, the number of holes drilled decreased. The experiment's results, especially regarding acoustic performance, emphasised the need to optimise spindle speed, feed rate, and tool diameter to improve both drilling efficiency and the lifespan of the tool.

Mittal *et al.*[18]: An experiment was conducted on titanium alloy using uncoated and amorphous carbon-coated tools with a 400-micron diameter to examine how different cutting parameters affected coating damage and debonding. The tools were tested at high speeds (100,000 RPM) with a 40-micron DOC and FR up to 4 µm/flute across different cutting lengths (20, 40, 60, and 80 mm). The amorphous carbon coating was applied using a specialised sputtering system. Results showed that both coated and uncoated tools failed after 80 mm of cutting. The debonding areas on the tool's rake and flank faces increased significantly with longer cuts, especially with higher feed rates. The critical failure force was 8700 N/mm². Coated tools showed a reduction.

In cutting forces (21-64 % less), as the coating reduced friction and prevented direct tool-workpiece contact. This also led to a smoother surface finish, with a 47% to 49%

decrease in surface roughness compared to uncoated tools. The amorphous carbon coating improved the cutting process by lowering friction, reducing heat buildup, and enhancing tool life, while increasing feed rates caused more debonding.

Mittal *et al.*[19]: An experiment was conducted on titanium alloy using tungsten carbide tools with different coatings: uncoated, and coatings of TiAlN and TiAlSiN, and solid lubricant WS2. The edge radius of the uncoated tool was around 1.5 µm, which increased to approximately 3.3 µm with TiAlN and TiAlSiN coatings and to about 3.8 µm when WS2 was added. The friction coefficients for TiAlN and TiAlSiN were 0.71 and 0.56, respectively, leading to expectations of reduced cutting forces for TiAlN. However, the increased edge radius from the coatings led to higher cutting forces. The highest flank wear was observed in the TiAlN-coated tool, resulting in increased force, while the lowest flank wear was seen with TiAlN + WS2. The addition of WS2 resulted in a 60% reduction in cutting forces (Fx) and a 70% reduction in feed forces (Fy) for TiAlN-coated tools, but no similar force reduction was observed with the WS2 coating on TiAlSiN tools.

Khare *et al.*[20]: The experiment on tool life in micro milling of stainless steel with a 500-micron micro tool demonstrated distinct wear phases, categorised into three stages: in Phase 1 (0-12.5 % life), the tool experiences minor rounding of the cutting edges and slight flank wear, with average cutting forces of 2.45 N; in Phase 2 (12.5%-70%), edge chipping occurs, and cutting forces rise to 4.17 N; in Phase 3 (70%-100%), severe breakage and chipping of the cutting edge lead to further increases in forces, reaching 4.93 N. Edge chipping was the dominant wear mechanism, and tools with sharp cutting edges were more prone to quicker wear. A significant tool life predictor was the use of Random Forest models, which analysed data like cutting forces and wear patterns, providing reliable predictions of tool failure even with complex, nonlinear relationships. The study highlights the role of edge radius in wear progression and the effectiveness of machine learning in forecasting tool life stages. These findings align with previous research, confirming that tool wear, particularly edge chipping, significantly affects tool longevity, and suggest that monitoring cutting forces and tool geometry is essential for optimising micro-milling processes.

Alam *et al.*[21]: An experiment was conducted on titanium alloy using a Central Composite Design (CCD) L20 to develop an RSM model for optimising parameters of machining. The experiment utilised a 2mm diameter, 4-fluted uncoated carbide tool in dry machining conditions. The cutting parameters included a low cutting speed of 62.83 m/min, feed rate of 20 mm/min, and DOC of 10 mm, as well as a high Vc of 157.08 m/min, feed rate of 50 mm/min, and DOC of 30 mm. A total length of 31.59 mm was machined for each experimental run, with machining time varying between runs. The results showed that higher cutting speeds led to lower surface roughness (Ra), while the axial DOC had minimal impact within the selected cutting parameter range. The optimal results were found within the cutting speed of up to 157.08 m/min. The surface roughness decreased when the cutting speed increased to 137.86 m/min, especially at lower DOC. Additionally, surface roughness improved when the feed rate was between 25 and 37 mm/min, with a minimal depth of cut. A successful quadratic model was developed, with a ramped function graph indicating that the best parameters were speed of 109.919 m/min, feed rate of 23.173 mm/min, and DOC of 16.396 mm. The model demonstrated good fit and predictive capability for optimising machining conditions on titanium alloys.

Dehena *et al.*[22]: An experiment was conducted on Brass using a 4-fluted cemented carbide tool with a diameter of 1.5 mm to evaluate the effect of using new and worn tools on cutting forces and surface roughness during up and down milling operations. The machining parameters included cutting speeds up to 100 m/min, feed rates of 5, 10, and 15 µm, and a constant DOC of 50 µm. The study was conducted under dry conditions. The tool diameter measurements for the new and worn tools were 1482.7 µm and 1475.1 µm, respectively, indicating that the worn tool was 7.6 µm smaller than the new one. The results showed that cutting forces were higher with the worn tool due to the larger cutting edge, which led to a negative rake angle. In both up and down milling operations, the cutting forces increased with the feed per tooth. For the new tool, cutting speed had minimal effect, while for the worn tool, the cutting force remained relatively unaffected by cutting speed but increased with feed per tooth. In down milling, the surface roughness increased with the feed per tooth, whereas in up milling,

surface roughness decreased with higher feed rates and cutting speeds. Overall, FR was found to increase cutting forces, while cutting speed tended to reduce them. This highlights the impact of tool wear on cutting performance, with worn tools leading to higher forces and surface roughness, while new tools demonstrated more consistent and efficient cutting behaviour across varying machining parameters.

Liang *et al.*[23]: The experiment focused on studying burr formation in Y-shaped microchannels on Aluminium 6061, using an uncoated micro end mill tool. The machining conditions were varied using a central composite design with spindle speeds of 8000, 14000, and 20000 rpm, FR up to 150 mm/min, and DOC up to 80 µ. Two different tool diameters (2 mm and 4 mm) were used in dry conditions. The study observed that burr formation was more pronounced at lower spindle speeds due to the ploughing effect, where material was displaced instead of effectively cut. At higher feed rates, burr size increased, with the depth of cut having a significant effect, as it led to thicker uncut chips and more material movement across the tool's rake face. Burr formation also varied with the geometry of the microchannels; in straight channels, burrs were larger at lower feed rates, while in curved channels, higher feed rates produced more burrs due to the curvature effect. The optimal conditions for minimising burr formation were found at a moderate SS of 14,000 RPM, a FR of 90 mm/min, and a moderate DOC of 50 µm, which resulted in the smallest burrs. In contrast, the largest burrs occurred with a moderate SS, a higher FR, and a low DOC.

3.0 Selection of Tools

The choice of material for cutting tools plays a key role in how well micro-milling processes perform. Tungsten carbide (WC) is one of the most commonly used materials for micro tools, mainly because it is very hard and has properties like high wear resistance. This helps the tool maintain a sharp cutting edge, even at high temperatures. Tungsten carbide is particularly effective when used on tough, abrasive materials, making it ideal for micro-milling, where tools face significant stress[24].

Its wear-resistant nature is especially important for high-speed, high-precision tasks like micro-milling, where tools can quickly wear out or become damaged. In addition, tungsten carbide's ability to withstand heat helps keep cutting edges intact at higher temperatures, extending tool life and ensuring consistent performance over long machining periods.

Recent studies have shown that while tungsten carbide tools are generally durable, they can still wear out when used on challenging materials like aluminium alloys. To address this, advances like cryogenic treatments and coatings have been developed, significantly boosting tool lifespan and improving machining performance.

4.0 Theoretical Background

4.1 Tungsten Carbide Tools

Tungsten carbide (WC) is a popular material for cutting tools, especially in high-precision applications like micro milling, due to its exceptional durability. It is made from a combination of tungsten and carbon, resulting in a hard, dense, and wear-resistant material. Tungsten carbide is highly valued in machining because of its ability to withstand extreme forces and temperatures, with hardness ratings typically between 8.5 and 9.0 on the Mohs scale. Research has shown that tungsten carbide retains its sharp cutting edge even at high speeds, which is crucial in micro milling, where cutting speeds are high, and the workpieces are small. Along with its hardness, tungsten carbide also has high thermal conductivity, allowing it to effectively dissipate heat and reduce thermal deformation. This property helps maintain tool performance over extended periods, which is especially important in micro-manufacturing, where precision and tool life are critical.

However, despite its benefits, tungsten carbide tools are still prone to wear when machining difficult materials like aluminium alloys. As a result, various techniques, such as cryogenic treatment and coatings, have been developed to improve its performance and durability[25,26].

4.1 Cryogenic Tools

Cryogenic treatment involves cooling the tool material to very low temperatures, typically below -150°C, which causes changes in its internal structure. In tungsten carbide, this process transforms the retained austenite

into martensite, a phase that improves the material's hardness, wear resistance, and toughness. This treatment significantly boosts the efficiency of the tool, especially for precision tasks like micro milling.

Studies have shown that cryogenic treatment increases the lifespan of tungsten carbide tools by reducing wear, cracking, and micro-chipping during machining. Additionally, it enhances the stability of the cutting edge at high spindle speeds, which is important for working with small features in micro milling. The process also reduces friction, leading to lower cutting forces and better surface finishes, making it particularly useful for both ferrous and non-ferrous materials[16,25].

4.3 Coating Techniques for Tungsten Carbide Tools

In addition to cryogenic treatment, surface coatings are often applied to further improve the performance of tungsten carbide tools. Coatings like TiN, TiAlN, and DLC have been studied for their ability to enhance wear resistance, reduce friction, and extend tool life. These coatings form a protective surface layer that shields the tool from wear and tear caused by friction during cutting[8].

TiN is commonly used because it has high hardness, good thermal stability, and excellent wear resistance. It also helps reduce friction, which prevents excessive heat buildup, thus improving tool life. For high-speed machining, TiAlN coatings are preferred due to their superior heat resistance, making them better suited for high-temperature cutting environments, such as micro milling. DLC coatings are another option gaining popularity, known for their very low friction and high hardness. They help reduce tool wear and improve surface finishes by providing a smooth, hard surface that minimises material transfer during machining. These coatings are especially beneficial for micro-manufacturing applications, where surface finish and tool longevity are critical[8,26].

Research has shown that combining cryogenic treatment with coatings like TiAlN creates a synergistic effect, significantly enhancing tool performance. This combination increases wear resistance and thermal stability, making tools more effective for high-precision tasks like micro milling[27,28].

Introducing Coating layers on tungsten carbide tools leads to reduced friction, which leads to low heat generation between the tool and workpiece, which enhances the overall tool life of the tool, improves tool performance and cutting efficiency of the tool. The head decipation is moderate in coated tools, whereas in cryogenic-treated tools, as the coating may get damaged, exposing the tool edge[20].

Tool treatment significantly influences machining performance across various parameters. Untreated tungsten carbide tools operate effectively at spindle speeds between 10,000 to 50,000 rpm, offering a tool life of around 100 hours and producing a surface roughness of approximately 1.2 µm, with a relatively low material removal rate. In contrast, cryogenically treated tungsten carbide tools support higher spindle speeds of 20,000 to 60,000 rpm and demonstrate improved performance with a longer tool life of 150 hours and finer surface finish of 0.5 µm, while maintaining a moderate material removal rate. Coated tungsten carbide tools are optimised for high-speed applications, functioning efficiently at speeds above 50,000 rpm. These tools exhibit a tool life of about 140 hours and produce a smooth surface finish

Table 1. Difference in Various tool treatments based on allowable input and expected outputs[25]

Tool treatment	Spindle speed (RPM)	Tool life (Hours)	Surface roughness (µm)	Material removal rate (cm^3/min)
Untreated tungsten carbide	10,000-50,000	100	1.2	Low
Cryo-treated tungsten carbide	20,000-60,000	150	0.5	Moderate
Coated tungsten carbide	50,000+	140	0.6	High

Table 2. Difference in different tool treatments based on advantages, limitations and key applications[26]

Treatment type	Advantages	Limitations	Key applications
Untreated	Cost-effective, high thermal conductivity	Rapid wear, poor heat management, and BUE issues	Low-speed and short-duration machining
Coated	Reduced friction, better wear resistance	Coating delamination, brittleness at stresses	High-speed machining of lightweight alloys
Cryogenically Treated	Enhanced toughness, lower wear, improved thermal stability	Requires precise control, process variability	High-precision and abrasive environments

Table 3. Focus and key benefits in processes[25,26]

Research Focus	What It Involves	Expected Benefits
Improved Tool Materials and Coatings	Looking into new materials and coatings that can make tools more durable and heat-resistant.	Longer-lasting tools, less wear, and smoother finishes.
Combined Machining Methods	Mixing micro milling with other methods like laser or electrochemical machining to enhance performance.	More efficient processes, less force needed, and higher precision.
Optimising Micro Milling	Customising micro milling techniques for industries like aerospace, medical devices, and electronics.	Better performance tailored to the needs of each industry.
For Specific Industries		
Real-Time Monitoring and Predictive Maintenance	Creating systems to track cutting forces, tool wear, and surface quality in real-time, plus using digital models for maintenance predictions.	More efficient processes, reduced downtime, and the ability to predict when maintenance is needed.
Eco-Friendly Practices in Micro Milling	Exploring the use of environmentally friendly lubricants, recycling cutting fluids, and combining additive and subtractive methods.	Reduced environmental impact, more sustainable practices, and less material waste.

of 0.6 µm, along with a high material removal rate. Each treatment offers a unique balance of durability, speed, and finish quality, tailored to specific machining requirements[26,29].

5.0 Future Scope

In the field of micromilling, several promising areas for further study have been identified. One important focus is the exploration of advanced tool materials and coatings. Researchers are looking into new materials that can enhance tool wear resistance and thermal stability, which would lead to improved tool life, reduced wear, and better surface finishes. Another avenue is the development of hybrid machining processes by combining micromilling with techniques like laser-

assisted machining or electrochemical machining. This integration could result in higher efficiency, reduced cutting forces, and improved precision. Additionally, process optimisation tailored to specific industries such as aerospace, medical devices, and electronics is crucial, aiming to enhance machining performance for specialised applications. The incorporation of real-time monitoring systems and the use of digital twins for predictive maintenance is another critical area, with the potential to improve process efficiency, reduce downtime, and enable predictive maintenance. Sustainability in micromilling is gaining importance, focusing on eco-friendly lubricants, recycling of cutting fluids, and hybrid additive-subtractive processes to minimise environmental impact, improve sustainability, and reduce material waste[25,26,30,31].

Carbon nanotube-reinforced tungsten carbide tools have been developed, offering enhanced hardness and wear resistance, which results in improved tool life and greater thermal stability. Another notable advancement is the use of nanocrystalline diamond tools, made from nanocrystalline diamond materials that offer superior hardness and wear resistance, extending tool life, reducing cutting forces, and achieving high precision in micromilling. Moreover a combination of plasma nitriding and cryogenic treatments has been applied to enhance surface hardness and fatigue resistance, further increasing tool lifespan and reducing wear rates.

Despite these advances, several research gaps persist in the micromilling domain. These include the development of new tool materials, particularly those reinforced with carbon nanotubes or made from nanocrystalline diamonds, to enhance tool performance, prolong tool life, and achieve better micromilling precision. There is also a need for further innovation in hybrid machining techniques, combining micromilling with laser-assisted or electrochemical methods, which can contribute to cutting force reduction and material capabilities expansion. Tailored process optimisation for specific industries such as aerospace and medical device manufacturing remains an area ripe for exploration to ensure industry-specific advancements. The integration of real-time monitoring through sensors, machine vision, and digital twin technologies is another critical research focus, aiming to improve process control, predictive maintenance, and tool life extension. A continued emphasis on sustainability in manufacturing is essential, particularly through the development of eco-friendly lubricants, energy-efficient processes, and recycling methods, helping to reduce environmental impacts, foster sustainable manufacturing practices, and lower operational costs[25,26].

6.0 Advantages of Micro-Milling

- *Faster Spindle Speeds*: Ultra-precision machines can achieve very high spindle speeds, which helps reduce cutting forces and create smoother surfaces. This is especially important for making tiny components with very fine surface details.
- *Stability and Precision*: These machines are built to minimise vibrations and prevent the tool from bending, ensuring consistent and accurate results, even at high speeds. This leads to higher quality and more precise parts.
- *Better Surface Finish and Accuracy*: Ultra-precision machines can produce parts with extremely smooth surfaces, often at the nanometer level, and meet very tight size requirements, reducing the need for extra finishing work.
- *Longer Tool Life*: With advanced cooling and lubrication systems, these machines reduce the wear on cutting tools, extending their life and minimising downtime, which helps keep costs down in micro-milling.
- *Ability to Handle Complex Shapes*: Thanks to their high precision, ultra-precision machines can easily tackle complex shapes and tight tolerances, making them perfect for micro-manufacturing in industries like medical devices, sensors, and electronics.

7.0 Conclusion

- DCT significantly enhances tool performance in machining Titanium alloy and AISI 11 steel by improving microstructure, hardness, bonding, and wear resistance, with DCT-24 providing optimal results and reducing grain size compared to untreated tools.
- Coated tools, such as TiAlN and TiSiN, improve surface finish, reduce burr formation, and extend

tool life by significantly enhancing surface quality and wear resistance.

- Tool failure mechanisms, including flank wear, Built-Up Edge (BUE), and chipping, are influenced by low feed rates that cause ploughing and increase tool wear, while DLC coatings minimise BUE and friction, reducing wear.
- Coated tools, particularly DLC and TiAlN, enhance surface quality by reducing friction, which extends tool life by minimising wear and improving performance over longer cutting distances.
- Monitoring cutting forces and wear patterns, combined with machine learning models, aids in predicting tool life stages, optimising machining operations.
- Proper optimization of spindle speed, feed rate, and depth of cut is essential for minimising tool wear and burr formation, with moderate settings effectively reducing burrs and improving machining quality.
- MQL and cryogenic pre-cooling reduce burr formation and tool wear while improving surface finish, especially in hard materials like Inconel and titanium.
- High speeds and FR increase cutting forces and tool wear but enhance Material Removal Rate (MRR) and surface finish when properly balanced with Depth of Cut (DOC).
- Appropriate coatings like TiSiN, TiAlN, and nACo optimise tool performance by extending tool life and reducing burr formation, while feed rate plays a key role in controlling surface roughness and burr formation during machining.
- Cryogenically treated tools wear out the least when machining aluminium alloys, outperforming both untreated and coated tools. Their durability and resistance to wear make them the best choice for long-lasting and efficient machining.
- Cryogenically treated tools last significantly longer than untreated and coated tools. This not only boosts efficiency but also reduces how often tools need to be replaced, highlighting their cost-effectiveness and practicality in machining.

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