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Comprehensive review of tool treatments and innovations in micro-milling precision and performance

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ABSTRACT

Advancements in micromilling, tool treatments, and ultra-precision machining centers have significantly enhanced the fabrication of micro-scale components across various industries. This paper provides a comprehensive review of recent developments in these areas, focusing on the impact of tool material innovations, surface treatments, and state-of-the-art machining centers on machining accuracy, surface finish, and tool longevity. The integration of advanced tool treatments and ultra-precision machining technologies has led to improved performance and expanded applications in fields such as biomedical engineering, electronics, and aerospace. The study discussed the need and advantages of tool coating, and cryogenic treatment on tools for efficient machining and enhancement of tool life. Future research directions were also discussed, emphasizing the need for continued innovation to meet the growing demand for high-precision micro-manufacturing.

Keywords: micro milling, tool treatments, ultra-precision machining, coatings, cryogenic treatment.

INTRODUCTION

Micro-milling has been described as a precision machining process characterized by machining tools measuring typically less than 1 millimeter in diameter, capable of producing very complex micro geometries and fine surface finishes on parts. The technology finds applications in industries that require high-precision parts, such as aerospace, medical devices, and microelectronics. The technology calls for the use of miniature tools for fabrication applications that involve complex features reaching micrometer tolerances. A particular aspect of micromilling that makes this process unique is that it can machine parts, small or large, usually resulting in microfeatures smaller than 1 mm, irrespective of the overall dimensions of the workpiece [1].

Micro-milling has an edge over other techniques like micro-turning or EDM (electrical discharge machining) with its superior high material removal rates and surface quality. It is capable of producing small parts with very good dimensional accuracy and a surface texture fine enough to meet stringent requirements dictated primarily by sectors such as medical, aerospace, and microelectronics industries. The development of ultra-precision high-speed machining canters has further magnified the contributions of micro milling toward superior accuracy of machining, hence making it one of the major micro-manufacturing processes. The material selection component in the cutting tool makes a significant impact on the performance and efficiency of micro-milling processes. One of the most often used materials for micro tools is tungsten carbide (WC); this is partly due to its hardness, and features such as high wear resistance and ability to keep a cutting edge sharp at high temperatures. Its high tolerance when applied in hard, abrasive materials enables it to endure normal stress conditions imposed in micro milling operations [2, 3].

Due to this feature, tungsten carbide is wear-resistant, which is significant to high-speed and high-precision processes like micro milling, in which the tool undergoes rapid wearing and risk of damage. Furthermore, the property of tungsten carbide, which proves its high thermal stability, guarantees that the cutting edges of tools at elevated temperatures are maintained, therefore prolonging the useful life of a tool and involving consistency in operation through long machining periods[5]. Recent investigation studies have found that tungsten carbide tools are nonetheless durable, exhibiting wear when subjected to machining difficult materials, like aluminum alloys. Thus, the development of tungsten carbide tools, including cryogenic treatments and coating applications, has undoubtedly increased the life of the tool and improved machining performance [3].

Cold treatments and other surface treatments have been well-researched and successfully employed. This involves subjecting the tool material to cryogenic temperatures – in this case, tungsten carbide, which accounts for improvements in hardness and wear resistance. The changes made by cryogenic treatment cause structural changes to the tool material, which has proven to have better toughness and reduced chances of cracks, thereby prolonging tool life and enhancing stability during machining. It is mainly effective in improving the performance of tungsten carbide tools within heavy-duty operations, such as micromilling hard metals and alloys [5].

Further, coating technologies have received major consideration in the literature as one of the ways to enhance the surface properties of cutting tools. Titanium-nitride (TiN), titanium-aluminum-nitride (TiAlN), and diamond-like carbon (DLC) are typically specified to tungsten carbide tools to reduce friction, increase thermal stabilities, and improve wear resistance. The coatings reduce heat from generation at the cutting edge, increase tool life, and improve surface finish quality by making it possible for tools to retain sharp edges. For example, TiAlN coatings significantly increase the wear resistance of tungsten carbide tools, making them well-suited for precision micro-milling applications at high speed and precision [3, 4].

Cryogenic treatment and coating not only increase the durability of tools but also add to the efficiency of the entire micro-milling operation with reduced tool changes and increased machining accuracy. When the treatments are combined, they can many times greatly extend the life of the tools and further improve the economics of micro-milling activities.

Purpose of the review

This review attempts at conducting a detailed assessment of the performance characteristics of micro milling operations in machining aluminum alloys using untreated, cryo-treated, and coated tungsten carbide tools. The review merged findings from different experimental studies to reveal how different treatments on tools affect important machining aspects such as surface roughness, cutting forces, and tool wear.

It further dealt with how input parameters like spindle speed, feed rate, and cutting depth affect machining performance and tool life in micro-milling applications. In addition, the paper addressed the importance of Ultra-Precision High-Speed Micro Machining Canters in achieving the extremely high spindle speeds required for efficient micro-manufacturing while providing a dynamic and stable platform for the high-precision micro-milling operation.

On the margins of this review, gaps in ongoing research were identified to cash-fund suggestions for future work such as developing novel coatings and treatments for tungsten carbide tools that could further boost performance levels in micro-manufacturing [6].

THEORETICAL BACKGROUND

Tungsten carbide tools

Cutting tools are machined mostly with the tungsten carbide (WC) material due to its very high durability and, in particular, it has become a preference among high-precision and high-performance applications such as micro milling. Tungsten carbide is a compound created from tungsten and carbon to form a very hard, dense, and wear-resistant material. Because of the hardness of tungsten carbide, it finds its place among the most preferred materials for cutting tools, because it withstands the extremes of forces and temperatures involved in machining operations, with the hardness usually being in the range of 8.5 to 9.0 on the Mohs scale. Long-term investigations of tungsten carbide have proven that it retains its cutting edge at speeds, which becomes important under micro milling conditions where tool performance is hampered in that instance by high cutting speeds coupled together with demands on small-scale machining [5].

Its superior hardness is complemented by high thermal conductivity through which cutting heat is dissipated effectively to minimize the occurrence of thermal deformation. Apart from this, the wear resistance attributes of tungsten carbide in the event of the use of such tools for an extended period produce consistent performance. Such tools are quite useful in micro-manufacturing applications, where tool life is crucial to maintaining precision [8]. However, even though there are all these benefits, tungsten carbide tools cannot avoid wear during the machining of difficult-to-cut materials such as aluminum alloys [5]. Hence, several efforts have been documented to modify the performance of tungsten carbide, such as cryogenic treatment, coating, etc.

Cryogenic treatment of tungsten carbide tools

Cryogenic treatment is essentially the process of bringing the tool material to very low temperatures, generally below -150 °C, which is capable of inducing phase transformation to enhance the material mechanical properties. It is evident in tungsten carbide where the changed carbide phase during cryogenic treatment converts the retained austenite in the tool microstructure to martensite. This phase transformation significantly improves hardness, wear resistance, and toughness, thus raising the efficiency of the tool, especially in the field of high-precision micro-milling applications.

Much research has been done on cryogenically treated tungsten carbide tools, which tend to perform better than untreated tools. It has been established that cryogenic treatment increases tool life through a reduction in the wear of tools and the generation of cracks and micro-chipping as a result of machining. Furthermore, it has been established that cryogenic treatment improves the stability of cutting edges at high spindle speeds for machining small features in micromilling [9].

Moreover, the cryogenic treatment also reduces the tool friction coefficient, resulting in reduced cutting forces and better surface finishes in micromilling operations. It has been successfully used in machining ferrous and nonferrous materials. Therefore, this is a suitable improvement for tools intended to produce compact components that require accurate tolerances in their manufacture.

Coating techniques for tungsten carbide tools

Surface coatings are usually applied in addition to cryogenic treatment. These coatings confer further performance enhancements to tungsten carbide tools. For example, Titanium Nitride, Titanium Aluminium Nitride, and Diamond-Like Carbon coatings have all been studied extensively with reference to their use in wear resistance improvement, friction reduction, and life extension of tools (Zhao et al., 2022). These coatings create a surface layer on the tool, further supplementing its wear and tear protection against the friction developed by the tool and workpiece [3, 4].

TiN is often employed because of its inherent high hardness, good thermal stability, and resistance to wear. However, the high friction-reducing quality of this coating during cutting really minimizes the heat generation for better wear resistance as compared to others. For high-speed machining, TiAlN coatings are favorable due to their improved high-temperature features in comparison to TiN. These considerations help to enhance the heat withstand capability of the tool during high cutting temperatures, hence improving the overall performance and efficiency of micro milling processes where heat dissipation is a major concern [3, 6].

Diamond-like carbon (DLC) coatings are another category of coatings attracting attention because of their very low friction and very high hardness capable of conferring tool wear reduction besides improvement in surface finish quality by providing a very smooth hard surface that minimizes material transfer while machining. These coatings are being evaluated favorably under micro-manufacturing applications, which are very sensitive to surface finish as well as tool life measurements. A demonstrated that a combination of cryogenic treatment and a coating (for instance, TiAlN) would synergistically enhance performance by increasing wear resistance as well as thermal stability, thereby making the tools apt for high-precision operations like micro milling [4].

Studies are available that discuss the adhesion and mechanical properties of TiAlN and AlTiN coatings deposited thicknesses 4–5 µm on a DMLS (Direct Metal Laser Sintered) titanium alloy substrate, that is commonly used in medical field. Titanium is prone to wear and reduced durability, leading to revision surgeries. To address this, surface modifications with coatings using PVD (Physical Vapor Deposition) technology have shown promise in increasing abrasion resistance. Both coatings exhibited smooth and dense structures with low surface roughness values The coatings demonstrated significantly higher hardness and elastic modulus compared to the substrate. TiAlN outperformed AlTiN with 21% higher elastic modulus and 16% higher hardness. [10]. Performance of surface coatings to improve wear resistance and reduce friction in industrial applications. The PVD coatings of TiN, TiCN, and TiAlN are usually used on cutting tools. It was found that TiN exhibited the lowest friction coefficient is 0.144 and the least wear, making it the most effective for applications requiring minimal wear and friction. TiCN showed higher friction but demonstrated significant durability, while TiAlN, despite excellent thermal stability, exhibited substantial wear under the same conditions. The study emphasizes the importance of choosing coatings based on specific operational needs, such as high-temperature environments or long-lasting tool performance [11]. There is a study stating the importance of multilayer deposition that examines the effect of nitriding AISI H13 steel before applying four multilayer PVD coatings of AlCrN, ZrN, TiSiN, and TiCrN at ambient and high temperatures between 20 °C and 700 °C. Nitriding significantly improved coating adhesion and wear resistance by creating a diffusion layer. Among the coatings, AlCrN showed the best wear resistance and lowest friction at ambient temperatures, while ZrN-based coatings (AlTiZrN + ZrN) performed exceptionally well at elevated temperatures with a friction coefficient as low as 0.12. TiSiN and TiCrN were less effective due to weaker resistance to high-temperature wear and oxidation. The findings suggest that combining nitriding with appropriate coatings can significantly enhance the lifespan and performance of industrial tools under varying conditions, especially in high-stress, high-temperature applications like forging dies and automotive molds [12].

Micromilling process overview

Micromilling is another very complex machining process that gives a better understanding of the interaction between the cutting tools and workpieces from machining parameters. In micromilling, one must try to remove the material as much as possible with less wear on the tool and at high precision and surface quality. These generally include the following parameters: spindle speed, feed rate, depth of cut, cutting tool geometry, and so forth, all affecting part quality (Figure 1).

This diagram illustrates the sequence of steps involved in micromilling, including tool engagement, material removal, chip formation, and surface finishing. Arrows connect the different steps, with tool parameters like speed, feed rate, and depth of cut labelled [5].

Spindle speed is the most critical parameter in micromilling, because high-speed rotations are needed in the process to overcome resistance in cutting small features. It also helps to minimize cutting forces, reduces the risk of tool deflection, and encourages good surface finish. Feed rate determines the speed at which the tool advances through the material and feeds it into the workpiece while causing tool wear when cutting material. The rate at which the tool advances through the material must therefore also be very carefully controlled while considering removal rate versus wear on tools. Cutting depth is among the most important parameters that affect tool wear and surface finish. In general, micromilling can be said to be traditionally practiced at shallow depths of cut to minimize tool forces and thereby the chances of tool breakage. However, deeper cuts could be necessary, depending on the part geometry and the material being machined [5].

Summary of tool performance enhancement

The jointly complementing cryogenic treatment and coating technologies are promising in improving performance by tungsten carbide tools during micro-milling. This treatment subsequently enhances the mechanical properties of the tools, rendering them efficient to withstand greater cutting forces and temperatures while enabling tool life and machining precision to be achieved. The influence of the cutting parameters, such as spindle speed, feed rate and cutting depth can also

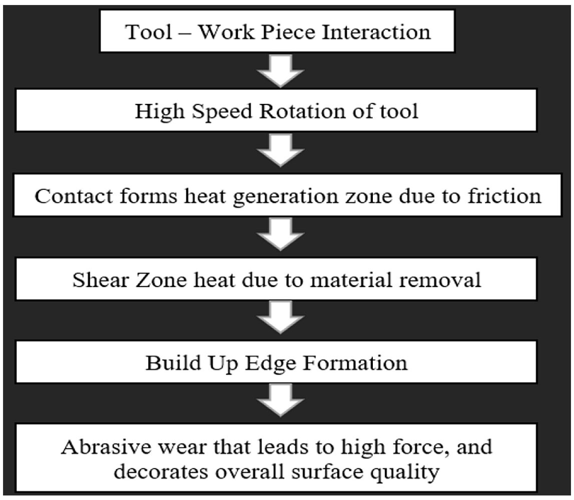

Figure 1. Micromilling process flow

not be overstated; they are crucial for the optimization of the micromilling process [5].

The advancement of these technologies ensures that tungsten carbide tools can meet the demands of modern micromilling operations, where high precision and efficiency are paramount.

EFFECTS OF TOOL TREATMENTS ON MICROMILLING PERFORMANCE

Untreated tungsten carbide tools

Such tools are usually made out of untreated tungsten carbide in micromilling operations because of their high hardness and wear-resistance properties. Unfortunately, the use of these tools is often limited, because they wear out and degrade thermally when tasked with high-speed high-precision machining. The cutting forces involved in micro-milling operations are large, and untreated tungsten carbide tools experience rapid wear, especially while manufacturing parts out of aluminum alloys [5, 13]. The effect of such wear is characterized by tool-chipping, rough surface finish, and premature failure of the cutting tools, thereby negatively affecting both the quality of the component produced and the life of the tool [9].

The major drawback of untreated tools in micromilling is rapid degradation due to the high stress and high temperature or heat developed while machining. Untreated tungsten carbide tools failed to show very little wear and deformation after a relatively short machining cycle, which was not favorable for surface finish as well as machining accuracy. Moreover, such untreated tools require frequent replacement, leading to considerable operational costs and downtimes in the manufacturing process. Thus, even though untreated tungsten carbide tools are good initial options for micro milling, their lack of wear resistance and part heat management limits their use, which calls for modelling the tool for performance improvements.

Cryo-treated tungsten carbide tools

Cryogenic treatment of tungsten carbide tools has a very well-established process to enhance the performance and life of precision cutting tools in micro-milling. Cryogenic treatment means such tools are subjected and maintained at very low temperatures (typically lower than -150 °C), resulting in the microstructure of tungsten carbide transforming, thus converting retained austenite into stable and harder martensite. Thus, performance-wise it affects the hardness, wear resistance, and toughness of the tool and it enables proper functioning under very rigorous micromilling conditions.

The positive effects of cryogenic treatment on the micro-milling performance of tungsten carbide tools have had many studies. Cryogenically-treated tungsten carbide tools had a lifetime increase of up to 30% as compared to the untreated ones in the machining of aluminum alloys [5, 13]. The treatment showed less micro-chipping, lesser wear, and superior surface quality of the workpiece. The treated tools were also shown to reduce the coefficient of friction between the tool and the workpiece: this, in effect would lower cutting forces and increase the efficiency of the overall micro-milling process.

The tools treated through cryogenic technology sustain their sharpness for a long time important in micromilling applications where precision is of paramount importance. Improved wear resistance, together with the thermal stabilization of cryo-treated tools, enables the use of higher spindle speeds without losing cutting efficiency, which makes them very convenient for high-speed micromilling operations. Therefore, cryogenic treatment extends tool life but also improves the surface finish and dimensional accuracy of the machined part.

Coated tungsten carbide tools

The titanium nitride (TiN), titanium aluminum nitride (TiAlN), and diamond-like carbon (DLC) coatings are frequently applied onto tungsten carbide tools in order to further enhance their performance concerning micromilling. The coating creates a protective layer on the tool surface that makes it more wear-resistant, less frictional, thermally stable, and thus applicable in high-speed, high-precision machining operations [6].

Among the well-known coatings, TiN is renowned for its hardness and high resistance to wear, besides improving the tool performance by lowering both friction and thermal conductivity. Research demonstrated that TiN-coated tools possess superior properties over untreated tungsten carbide in terms of resistance to wear and cutting force reduction. TiAlN coating, being one of the most effective at high temperatures, is extensively used in micro-milling operations where elevated cutting temperatures are obvious. Under severe conditions, these coatings maintain the sharpness of the tool, thereby prolonging its lifespan and increasing efficiency in machining [3, 4].

DLC coatings also find an application for the improvement of tungsten carbide tools. Due to their extremely low friction coefficient, these coatings help reduce tool wear while improving surface quality through limiting material transfer between the tool and workpiece. In the applications using high-speed micromilling, tungsten carbide tools coated with DLC have significantly enhanced surface finish and accuracy of machined parts. Because of the high hardness and smoothness of DLC coatings, they can be used in working with delicate materials, where a precise surface finish is very important [5].

The beneficial aspects become more vivid when cryogenic treatment and coating are used jointly. The best performances of tools would be recorded when both treatments were applied, improved cryogenic treatment and TiAlN coating. Such treatment will impart enhanced wear resistance and thermal stability to tungsten carbide tools for micro-milling applications in the machining of aluminum alloys. Consequently, the tools require less frequent changing, and consequently, this means that it reduces tool downtime and makes micromilling processes quite cost-effective [5].

Comparison of tool treatments

The effectiveness of untreated, cryo-treated, and coated tungsten carbide tools was analyzed in micromilling. The cryogenic treatment and coating both go a long way to enhance the performance of the tools. Initially, untreated tools work, but after some time, while wearing quickly, cutting force increases, and surface finish goes down; cryo-treated tools show an improvement in hardness, resistance to wear, and time, which makes them ideal for high-performance micro milling (Table 1).

Among these are the differences between the coatings: coated tools with TiAlN and DLC showed superior wear resistance, lower friction, and higher thermal stability to accommodate high-speed micro milling work. Coatings, together with cryogenic treatments, are further optimization techniques to ensure improved performance for micromilling operations where accuracy and tool life are prime issues. This would greatly depend on the machining needs, such as the material to be machined, the complexity of the part, and the required surface quality (Table 2, Figure 2) [6]. This bar chart compares the performance of untreated, cryo-treated, and coated tungsten carbide tools on key metrics like wear resistance, surface roughness, and tool life

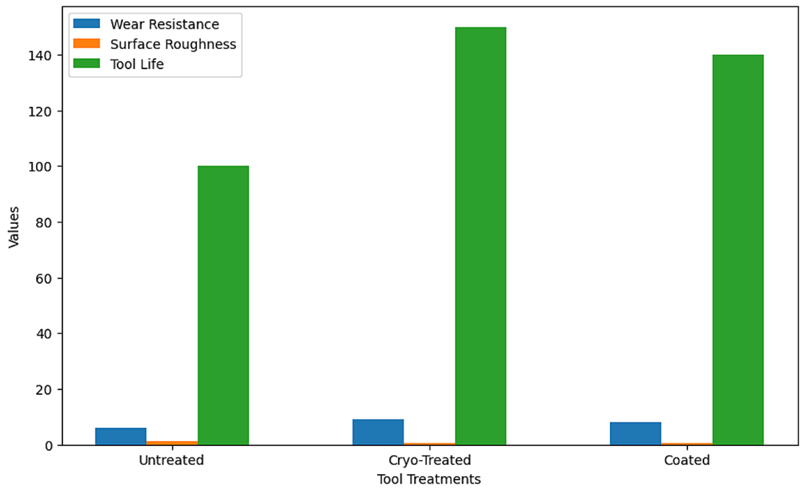

Figure 2. Tool treatment comparison (wear resistance, surface roughness, tool life) [5]

Table 1. Comparison of tool treatments in micromilling [15]

Tool treatment	Wear resistance	Surface roughness (µm)	Tool life (hours)	Cutting force (N)
Untreated tungsten carbide	Moderate	1.2	100	High
Cryo-treated tungsten carbide	High	0.5	150	Low
Coated tungsten carbide (TiN, TiAlN)	Very High	0.6	140	Moderate

Table 2. Tool performance enhancement with coatings and cryogenic treatment [16]

Treatment combination	Wear resistance	Surface finish	Tool life	Cutting force reduction
Untreated tungsten carbide	Moderate	Moderate	100 hrs	None
Cryogenic treatment	High	Improved	150 hrs	Moderate
Coated tools (TiAlN, DLC) + cryogenic treatment	Very high	Excellent	180 hrs	Significant

Summary of tool treatment effects on micromilling performance

Untreated tungsten carbide tools: Effective, but limited in terms of wear resistance and thermal stability, requiring frequent replacements.

Cryo-treated tungsten carbide tools: Significant improvement in wear resistance, tool life, and surface quality, especially in high-speed micro-milling applications. Coated tungsten carbide tools: Superior wear resistance, reduced friction, and improved thermal stability, making them ideal for demanding micro-milling operations.

Integration of cryogenic treatment with coatings will enhance the performance of tungsten carbide tools. This would be a total answer regarding the obstacles in micro-milling. It not only helps in lowering the costs of machining but also increases tool life as well as improves surface finish and precision.

INFLUENCE OF CUTTING PARAMETERS ON MICROMILLING

Spindle speed and cutting forces

Spindle speed is really important in micromilling as it creates direct effects in terms of cutting forces and tool life. This is where it becomes more important in micro-manufacturing processes where high speeds are necessary to overcome the resistance due to the small cutting edges and also effective material removal. Studies have shown lower cutting forces and increased surface finish with a decrease in tool deflection at higher spindle speeds. For example, they reduced radial cutting forces of increased spindle speed and almost completely eliminated burr formations, which are quite common in micro-machining operations [17, 18].

On the other hand, high spindle speed decreases the cutting force and increases the thermal load in the cutting tool. Hence, heat generation control becomes vital to avoid tool wear and failure. To solve the problem, cryogenic treated or coated tools are used to enhance the thermal stability of the tool, keeping sharp edges even at high speeds. Thus, not only is it important for the cooling system to ensure optimum temperature during high-speed micromilling, but also that the forces cut and life of tools is further minimized.

Moreover, it is better in finer surface quality because there are good impacts reduced from vibrations and tool chatter. Micromilling is sensitive to those small tool motion chatter; thus, high-speed rotation helps maintain the precision required for fine features with the least amount of surface roughness.

Feed rate and cutting depth

The manipulation of feed rate as well as cutting depth amounts to other essential parameters toward material removal rates, wear of the tool, and surface finish-in micromilling operations. Feed rate is the speed with which a tool follows across the workpiece whereas a cutting depth is defined as the thickness of material removed at one pass [22].

It can be said that by simply increasing the feed rate, the material removal rate also increases, but the downside is raising the cutting force requirement which in turn results in tool wear. A high feed rate, for instance, might place an excessive load on the cutting tool and damage the tool itself. It can happen when using untreated tungsten carbide tools. Lower feed rates, on the other hand, help prevent these high cutting forces from acting on the tool and result in finer surface finishes with prolonged tool lives; however, decreased material removal rates result from such feed rates. Hence, the balance is what would ensure efficiency in material removal rate with an effective tool [23].

Cutting depth can be defined as the amount of material removed in each pass directly. Most of the time in micro milling, shallow depths are preferred for cutting, and this is because shallow depth will cause smaller cutting forces and also reduce tool deflection. Sometimes, deeper cuts may be required due to a particular shape or a larger feature on the sample being worked on. In such a situation, it becomes very important that other parameters, like feed rate, spindle speed, etc., be altered considering the increased cutting force created so that tool wear can be reduced. Cutting depth and feed rate control can work together to minimize tool wear and damage while still accomplishing a reasonable material removal rate. They have identified synergetic optimizations of cutting depth and feed rate parameters that could be paired with a suitable tool treatment such as cryogenic or coating treatment, which can greatly improve machining efficiency and even reduce operation costs [25].

Role of tool geometry in cutting performance

The geometry of cutting tools is perhaps the most critical factor in efficient micro-milling operations. Unlike conventional milling, micromilling relies on extremely small diameter tools, so even minor variations in cutter geometry might result in significant changes in forces imposed on the surface, surface quality, and tool life. The different geometries of the tools include diameters, rake angles, clearance angles, and edge radii.

For micromilling, small cutting-edge radii are preferred to facilitate high precision and fine surface finishes. However, if the cutting-edge radius is small, then it causes severe tool wear, due to increased stress concentration at the cutting edge. Hence, a compromise has to be achieved between precision and tool durability, which is the reason why tungsten carbide tools are the most preferred ones since they are treated with coatings or cryogenically treated for edge sharpness preservation while bringing no compromise on tool life [6].

Rake angle also influences the cutting forces and chip formation, as it is stated that the positive rake angle can decrease reductions in cutting forces associated with the chip removal process and thus improve the surface finish. On the other hand, it gives higher values of induced cutting forces, leading to tool deflection or bad surface quality. Tool geometry should be optimized with parameters such as spindle speed, feed rate, and cutting depth to achieve optimum results in micromilling operations (Figure 3) [9]. This graph shows the relationship between cutting force and tool life, comparing untreated, cryo-treated, and coated tools [5].

Effect of tool wear on cutting parameters

Tool wear is a normal fact that happens naturally with machining and is mainly the result of the continuous contact of the cutting tool and workpiece. As the tool continuously wears away, its cutting efficiency is reduced, thereby resulting in high cutting forces, poor surface finish, and increased tool wear. The wear is a major influence of several factors, such as cutting parameters, tool material and type of coating or treatment done on the tool [26].

Micromilling tool wear is even more critical, because the tools have small cutting edges,

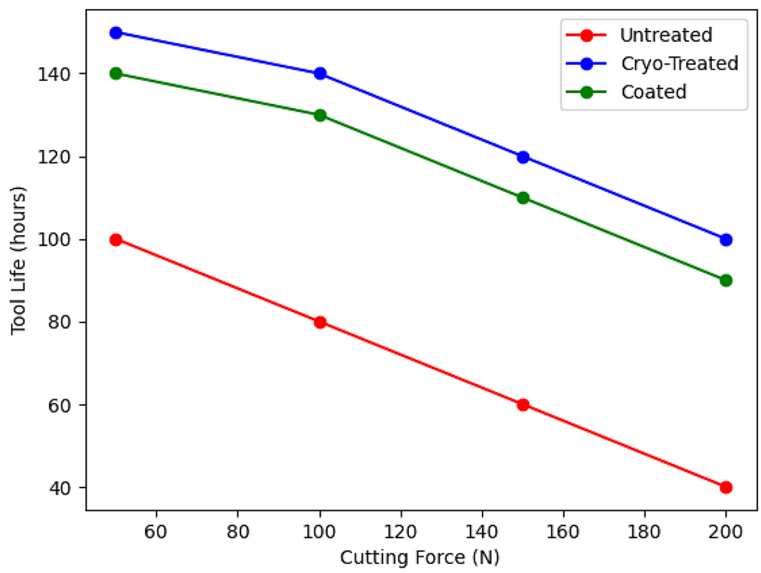

Figure 3. Tool life vs cutting force:

and therefore even minor wear could alter the performance in machining. Many investigations show that with higher spindle speeds and aggressive cutting parameters, the rate of tool wear is increased especially when untreated tools are used. In contrast, cryogenically treated and coated tools exhibit much slower wear rates, allowing for longer machining cycles and more consistent results (Figure 4). This line graph shows tool wear progression over time for untreated, cryo-treated, and coated tools, highlighting how each treatment affects tool longevity [5].

It is necessary that tool wear should be periodically monitored in micromilling operations, since excessive wear might give rise to part defects and escalation in operational costs. By using advanced tool treatments and optimizing cutting parameters, tool wear could also be reduced, thus improving the efficiency and productivity of the micro-milling process (Table 3, 4).

Summary of cutting parameter effects

Spindle speed – higher spindle speeds reduce cutting forces and improve surface finish but can increase tool wear due to higher temperatures. Cryogenic treatment and coatings help mitigate thermal load and extend tool life.

Feed rate and cutting depth: a higher feed rate increases material removal but also leads to higher cutting forces and tool wear. Shallow cutting depths help reduce cutting forces, while deep cuts require careful adjustment of parameters to avoid excessive wear.

Tool geometry – tool geometry significantly affects cutting forces, surface finish, and tool life.

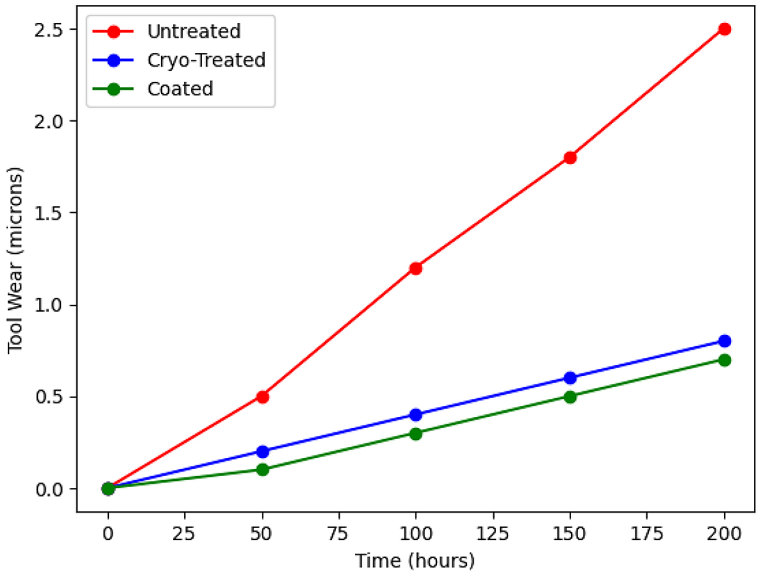

Figure 4. Tool wear comparison over time

Table 3. Effect of spindle speed on micromilling performance [6]

Spindle speed (RPM)	Cutting force (N)	Surface roughness (µm)	Tool wear rate (µm/hr)	Material removal rate (cm^3/min)
10.000	High	1.2	High	Low
20.000	Moderate	0.8	Moderate	Moderate
50.000	Low	0.5	Low	High

Table 4. Feed rate and cutting depth impact on tool wear and surface finish [7]

Feed rate (mm/min)	Cutting depth (mm)	Tool wear (µm)	Surface roughness (µm)	Material removal rate (cm^3/min)
10	0.05	Low	High	Low
20	0.1	Moderate	Moderate	Moderate
40	0.2	High	Low	High

A balance must be achieved to ensure high precision while minimizing wear.

Tool wear: tool wear is inevitable, but by optimizing cutting parameters and employing advanced treatments such as cryogenic treatment or coatings, tool life can be extended and machining performance improved.

The careful optimization of these cutting parameters is deemed essential for performing efficient, high-precision micromilling operations. Manufacturers can reduce tool wear and operational costs, while producing superior surface finishes and dimensional accuracies by altering spindle speed, feed rate, cutting depth, and tool geometry.

ROLE OF ULTRA-PRECISION HIGH-SPEED MICRO MACHINING CENTERS

Overview of ultra-precision high-speed micro machining centers

Ultra-precision high-speed micro machining centers are machines that operate in micromachining processes that call for the levels of precision achieved in micromilling. These machines would be able to maintain high stability in operations and accuracy and repeatability during highly dynamic operations while machining small, complex parts with geometries very specific to them. It is characterized by a spindle speed; precision motor control; and an advanced feedback system that allows the tool to retain its exact position during machining, even when subjected to dynamic loads [27].

This machine has high-speed spindles capable of working beyond speeds of 100,000 revolutions/min and can perform very highly efficient micromachining processes. The maintenance of such a high speed is important in performing micromilling operations, where the diameters of the cutting edge are small, and the prevention of sharp edges at higher speeds is imperative to give a smooth surface and very precise features. Ultra-precision machining centers also often come with advanced thermal management systems that subsist to lessen the heat generated by higher spindle speeds, which is vital in tool life and tool wear aspects [30].

These machines have very advanced features with respect to direct drives and high-precision encoders, further providing an unrivalled accuracy in positioning and movement. This is marked as high-precision control, which consequently allows for the uniform generation of soft details from the most challenging materials. Hence, such centers become ever more important when dealing with industries like aerospace, medical devices, and microelectronics, where part geometries very often require tolerances down to the micron range.

Advantages of micromilling

Ultra-precision high-speed machining centers offer several key advantages for micromilling operations [5]:

- higher spindle speeds: one of the prime advantages of these machines is that they can attain extremely high spindle speeds. It has already been discussed that the spindle speed is highly important in reducing cutting forces and improving surface finish in micromilling. Ultra-precision machines make possible the achievement of micro-components with very small surface roughness at very high spindle speeds, a critical requirement in many micromanufacturing methods.
- dynamic stability: these machining centers are equipped with specific design features to tackle vibrations and minimize tool deflection in high-speed machining processes, with an effect on micromilling. Even a small vibration can dramatically affect the quality of the finished product and create dimensional inaccuracies and poor surfaces for the product. High-speed micromachining centers are built with vibration-damping systems and rigid structures to maintain dynamic stability to provide consistent and accurate machining at even a very high cutting speed.
- improved surface finish and precision: ultra-precision machining centers have the capacity to produce parts with extremely fine surface finishes, often in the range of nanometers. This is highly relevant in micro-manufacturing, where surface integrity and smoothness are crucial to the overall functionality, especially in applications such as biomedical implants and microelectronics. The improvements in precision also mean that final part dimensions comply with required tolerances, and fewer secondary operations are required.
- enhanced tool life: these high-speed machining centers generally have good cooling and lubrication systems for the reduction of thermal loading on the cutting tools. Hence, tool wear is reduced, especially when machining

materials that produce considerable amounts of heat in cutting. Such machines are thereby capable of holding a steady and cooler environment and, therefore, prolonged life for cutting tools, which is especially beneficial in micromilling, considering frequent changes of tools would normally result in high costs and increased downtime due to the frequent changes required.
- flexibility in complex geometries: ultra-precision machining centers, having high precision and stability, make it a perfect choice for machining complex part geometries exhibiting tighter tolerances. They can also produce the elaborate profiles and the delicate features needed for micro-manufacturing, e.g., those are found in the applications of medical devices, sensors, and microelectronics, where conventional methods are not as useful. (Table 5 and 6).

This plot shows the relationship between cutting speed and surface roughness for different tool treatments, highlighting how increasing spindle speed can improve surface finish (Figure 5).

Integration of advanced tool materials with ultra-precision machining centers

Significant improvement in machining performance can be achieved through high-speed

Table 5. Key advantages of ultra-precision high-speed micro machining centers [6, 7]

Feature	Description	Benefits
High spindle speeds	Spindle speeds up to 100,000 rpm or more	Reduced cutting forces, improved surface finish, faster processing
Dynamic stability	Advanced vibration damping and rigid structure	Improved machining precision and reduced tool deflection
Thermal management systems	Integrated cooling systems for heat dissipation	Reduced tool wear, and maintained cutting efficiency at high speeds
Precision control	High-resolution encoders and feedback systems	High accuracy and repeatability in machining operations

Table 6. Comparison of tool performance with ultra-precision machining centers [6, 7]

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

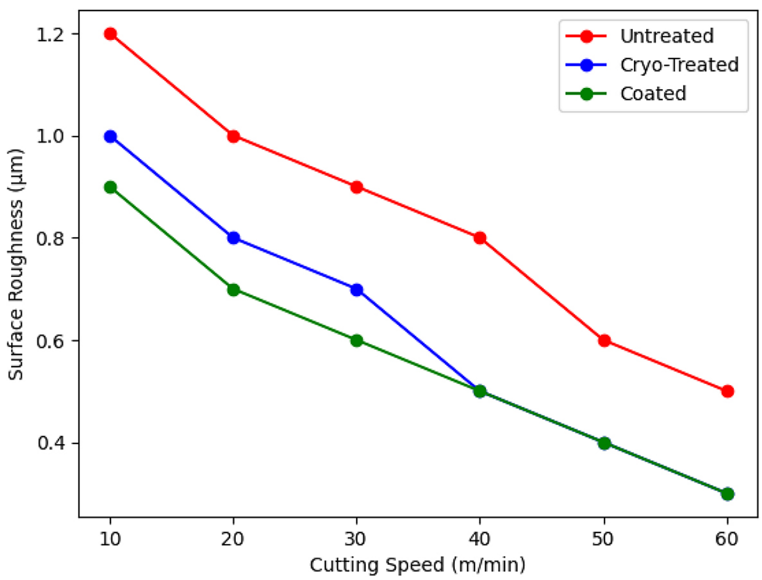

Figure 5. Micromilling surface roughness vs cutting speed [5]

ultra-precision micro machining centers combined with appropriate tool materials, especially cryogenically treated or coated tungsten carbide tools. High spindle speeds and accuracy show a realising potential for advanced tool materials. High tungsten carbide cryogenically treated with high-speed machining centers has dynamic stability and higher speeds to mitigate the wear and thermal degradation found in most high-speed operations [33].

Coated tools in general, especially TiAlN and DLC coatings, perform quite well when combined with high-speed micro machining centers. These coatings enhance the ability of the tools to withstand the high temperature and friction forces developed at increased spindle speeds, thereby ensuring longer tool life with subsequently high performance in machining. Such a combination of high-speed, high-precision machining with advanced tool materials provides a truly promising basis for attaining micro milling high performance [3].

Challenges and considerations

Ultra-precision high-speed micromachining centers have many advantages. However, these centers certainly have their challenges. One of the most important ones is related to machines being very expensive, which is a considerable investment for manufacturers. In addition, setting up and maintaining machines requires highly specialized knowledge and skills related to complex control systems and advanced programming techniques.

High spindle speeds and tight tolerances for micromachining mean that tool wear and machine stability have to be monitored very closely. A cut of just a few millimeters in setup or tool selection could result in contamination of the product. Therefore, the operator must possess good knowledge about the process being machined and maintain regular checks on machine conditions for excellent performance [36].

Summary of the role of ultra-precision high-speed micro machining centers

Ultra-precision high-speed micromachining centers dramatically enhance the performance capabilities and efficiencies of micromilling operations. These machines excel at achieving very high spindle speeds, while at the same time maintaining dynamic stability and surface finishes that ensure their suitability for micro components with very tight tolerances and very intricate geometries. Modern tool materials, such as cryogenically treated or coated tungsten carbide tools, promote even more capability by ensuring longer tool life, as well as enhanced machining accuracy. These machines are nevertheless not without problems; however, their exactness of measures, speeds, and efficiencies is why they are often viewed as unavoidable elements in modern micro-manufacturing applications.

FUTURE DIRECTIONS AND RESEARCH GAPS

Potential areas for further study

Most of these developments in the technologies of micromilling and treatments of cutting tools have left many topics for future research in order to enhance the process. One of the areas that will require more research is the provision of advanced coating materials and cutting tools. Although Ti-Al-N and DLC coatings have been successful in terms of longevity and wear resistance, newer coatings with more advanced properties, especially for high-speed micro-milling, can be explored. Coating such as one or two would be with high thermal stability, low friction, and wear resistance would offer better performance under extreme conditions pushing the current micro milling capabilities [5].

The result is a hybrid process that would go into more studies,because it becomes micro milling with other techniques such as laser-assisted micro milling or electrochemical micro milling. These hybrid processes promise to add the capability of reducing cutting forces, improving surface finish, and machining complex or tougher materials with minimal tool wear at large. In this way, for example, laser-assisted methods will reduce the thermal load on the tool mainly during high-speed cutting, increasing tool life and improving precision.

Moreover, there is a gap in research into optimizing the process parameters in micromilling for specific industries. While there may be general guidelines on how to control parameters like feed rate, spindle speed, and cutting depth, the specific applications for example, aerospace or medical implants or electronics manufacturing require further studies. These studies may consider different materials and requirements on tolerances and surface quality needed in each application. Optimization of the micromilling processes would involve, for instance machining of medical implants using biocompatible material or the machining of microcomponents for electronic circuits that have high-principled precisions, and that would provide an excellent capacity of advancement in manufacture (Table 7) [38].

Advances in tool materials and treatments

Further development of advanced tool materials, especially incorporating nanostructured features and composites, is a great potential area for future research. For instance, the carbon nanotube-reinforced tungsten carbide or nanocrystalline diamond tools should offer excellent hardness, wear resistance, and thermal stability, being suitable for micro-milling operations. These new materials should potentially eliminate the limitations of tungsten carbide tools, which are susceptible to damage and wear due to thermal effects during high-speed machining of tough materials.

The other area for research lies in the development of multi-step or multi-stage treatment procedures for cryogenic processing. While it has been established that normal cryogenic treatment improves tool properties, more gains in wear life and accuracy of machining may be obtained by investigating the effects of prolonged or multi-step cryogenic treatment. Apart from this, the combination of cryogenic treatment with other techniques such as plasma nitriding or shot peening may open entirely new possibilities for extending tool lives and optimizing machining performance in micromilling. Moreover testing multi coated and cryogenic treated and coated are still under study.

Improved measurement and monitoring techniques

An area where much can still be done is the development of improved measurement and monitoring techniques for micromilling. For more efficient and precise micromilling operations, one can think of real-time monitoring of cutting forces, tool wear, and surface quality by advanced sensors and machine learning algorithms. Integrated systems designed to include machine vision force and temperature sensors would give valuable feedback, which enables real-time automatic adjustments to cut parameters using acoustics. Optimization becomes continuous, thereby reducing tool wear, improving surface finish, and minimizing operational downtime [36].

In addition, the fusion of digital twins that mirror the machining process basically virtual models of machining where real-world conditions are recreated would facilitate more reliable predictions about tool performance and machining outcomes. This will help manufacturers adjust cutting parameters for optimizing their operations, forecast tool failure before it happens, and thereby have higher efficiency in the process. As the digital curve continues maturing, implementation in micromilling will redefine the future state of this precision machining, where adaptability and reliability become the qualities expected (Table 8).

Sustainability in micromilling

A significant improvement in sustainability in the micro-manufacturing operations would come from investigating the various ways of: reducing energy consumption, minimizing material waste, and improving recycling in the cutting fluids used during micro milling. One area that requires a worthwhile

Table 7. Potential areas for further study in micromilling [5, 20]

Area of research	Description	Potential outcomes
Advanced tool materials and coatings	Exploration of new materials and coatings for enhanced tool wear resistance and thermal stability	Improved tool life, reduced wear, and better surface finishes
Hybrid machining processes	Combining micro milling with techniques like laser-assisted machining or electrochemical machining	Higher efficiency, reduced cutting forces, improved precision
Process optimization for specific industries	Optimizing micromilling for industries such as aerospace, medical devices, and electronics	Improved machining performance for specific applications
Real-time monitoring and digital twins	Developing systems for real-time monitoring of cutting forces, tool wear, and surface quality, as well as the use of digital twins for predictive maintenance	Enhanced process efficiency, reduced downtime, and predictive maintenance
Sustainability in micromilling	Exploring eco-friendly lubricants, recycling of cutting fluids, and hybrid additive-subtractive processes	Reduced environmental impact, improved sustainability, and reduced material waste

Table 8. Advanced tool materials and treatments for micromilling [15]

Material/technique	Description	Expected benefits
Carbon nanotube-reinforced tungsten carbide	Tungsten carbide tools are reinforced with carbon nanotubes for enhanced hardness and wear resistance	Improved tool life, and enhanced resistance to thermal degradation and wear
Nanocrystalline diamond tools	Tools made from nanocrystalline diamond materials offer superior hardness and wear resistance	Extended tool life, reduced cutting forces, and high precision in micro-milling
Plasma nitriding + cryogenic treatment	Combination of plasma nitriding and cryogenic treatment to enhance surface hardness and fatigue resistance	Increased tool lifespan, reduced wear rates, and higher

Table 9. Summary of research gaps in micromilling [5]

Research gap	Potential research focus	Expected outcomes
Development of new tool materials	Exploration of materials like carbon nanotube-reinforced tungsten carbide and nanocrystalline diamond	Enhanced tool performance, longer tool life, and better precision in micro milling
Hybrid machining techniques	Combining micro milling with laser-assisted or electrochemical techniques	Improved cutting efficiency, reduced cutting forces, and expanded material capabilities
Optimization for specific industries	Tailored research for micromilling in aerospace, medical devices, and electronics industries	Industry-specific process optimizations and advancements
Real-time monitoring integration	Use of real-time sensors, machine vision, and digital twin technology for continuous process optimization	Improved process control, predictive maintenance, and enhanced tool life
Sustainability in manufacturing	Development of eco-friendly lubricants, energy-efficient processes, and recycling methods	Reduced environmental impact, more sustainable manufacturing processes, and lower operational costs

amount of research initiative is the formulation of green lubricants and coolants for efficient cooling that does not harm the environment [5].

Another promising area in this context could be the combination of additive manufacturing techniques with micro milling. The synergism of additive and micromachining could be the door for the production of quite complex micro-components with very limited material wastage, thus reducing the carbon footprint of the manufacturing process. It is expected that this hybrid application of the additive and subtractive methods-potential hybrid manufacturing systems might overtake the traditional system in producing richly customized, complex parts by focusing on sustainability [36].

Summary of research gaps

Advanced tool materials and coatings: continued development of cutting-edge tool materials and coatings to enhance wear resistance, thermal stability, and overall tool performance. Hybrid machining processes: exploration of hybrid processes, such as laser-assisted micromilling, to further improve tool life and machining efficiency.

Process optimization for specific industries: Focus on optimizing micromilling processes for applications in aerospace, medical devices, and electronics. Measurement and monitoring: development of real-time monitoring systems and digital twin technology to optimize machining performance and predict tool failure.

Sustainability in micromilling: research into eco-friendly lubricants, sustainable machining practices, and the integration of additive manufacturing with micromilling to reduce material waste and energy consumption (Table 9).

Further research is needed to bridge these gaps, which will definitely contribute towards improving micro-manufacturing as a whole. The advancement in tool materials and machining techniques along with the monitoring systems will enable the manufacturers to eliminate the current challenges and obtain greater precision, efficiency, and sustainability in future micromachining operations.

CONCLUSIONS

Advancements in micro-milling have significantly improved precision and efficiency in producing micro-scale components, particularly through innovations in tool treatments like cryogenic methods and coatings.

Tungsten carbide tools treated cryogenically exhibit up to 30% longer lifespan, improved surface finishes (reducing surface roughness to 0.5 μm from 1.2 μm), and better thermal stability compared to untreated tools. Coated tools with cryogenic treatment achieve 180 hours lifespan, outperforming cryogenic treatment alone (150 hours) and untreated tungsten carbide (100 hours), with excellent wear resistance and significant durability improvements.

Coated tools, especially with materials like TiAlN and DLC, provide very high wear resistance and a tool life of approximately 140–180 hours, depending on the combination of treatments.

Surface modifications using PVD coatings, such as TiAlN and AlTiN, significantly enhance the wear resistance, hardness, and elastic modulus of titanium alloys used in medical applications, with TiAlN demonstrating superior mechanical properties and durability over AlTiN.

The effectiveness of PVD coatings in industrial applications depends on specific operational needs, with TiN providing the lowest friction coefficient, TiCN offering high durability, and TiAlN excelling in thermal stability but showing more wear under similar conditions.

Multilayer deposition techniques, particularly when combined with nitriding, significantly improve coating adhesion, wear resistance, and performance across varying temperatures, with coatings like AlCrN and ZrN-based layers performing exceptionally well in high-temperature, high-stress industrial environments.

High-speed machining centers amplify these benefits, achieving spindle speeds above 50,000 RPM, which lowers cutting forces while enhancing surface finish and tool durability.

Additionally, optimizing cutting parameters like spindle speed, feed rate, and depth of cut can significantly reduce tool wear and operational costs, achieving balance between material removal rate and tool longevity. Moreover, further research is required in the field of coated cryogenically treated tungsten carbide tool and mixed type coated tools.

REFERENCES

1. Yong, A.Y.L., Seah, K.H.W. & Rahman, M. Performance of cryogenically treated tungsten carbide tools in milling operations. Int J Adv Manuf Technol 2007; 32, 638–643 https://doi.org/10.1007/s00170-005-0379-0
2. Çiçek, A., Kıvak, T., Ekici, E., Kara, F., & Uçak, N. Performance of multilayer coated and cryo-treated uncoated tools in the machining of AISI H13 tool steel—Part 1: Tungsten carbide end mills. Journal of Materials Engineering and Performance, 2021; 30(6), 3436–3445. https://ui.adsabs.harvard.edu/link_gateway/2021JMEP...30.3436C/doi:10.1007/s11665-021-05656-w
3. Anand, S., & Mathew, M. Optimization of cutting parameters affecting surface roughness in micro milling of Inconel 625 superalloy with cryogenically treated tungsten carbide inserts. SN Applied Sciences, 2021; 3(1), 1–11. https://link.springer.com/article/10.1007/s42452-021-04303-2
4. Muhammad, A., Gupta, M.K., Mikołajczyk, T., Pimenov, D.Y., Giasin, K. Effect of tool coating and cutting parameters on surface roughness and burr formation during micromilling of inconel 718, Metals, MDPI, 2021. https://doi.org/10.3390/met11010167
5. Rathod, V.P., Wankhade, S.H. A review on the impact of micro-tools on micro-milling outcomes for aluminium alloy. Advances in Science and Technology Research Journal, 2025; 19(3). https://doi.org/10.12913/22998624/200007
6. Baig, A., Khan, M.A., Jaffery, S.H.I., Khan, M., Naseer, R., Shah, I., Petru, J. Experimental evaluation of machinability of Monel 400 alloy during high-speed micro milling using various tool coatings, Advances in Science and Technology Research Journal, 2024. https://doi.org/10.12913/22998624/190624
7. Rinku K. Mittal, Ramesh K. Singha, Salil S. Kulkarnia, Praveen Kumarb, H.C. Barshiliab, Characterization of anti-abrasion and anti-friction coatings on micromachining response in high-speed micromilling of Ti-6Al-4V, Journal of Manufacturing Processes, Elsevier, 2018. https://doi.org/10.1016/j.jmapro.2018.06.021
8. Mittal, R.K., Kulkarni, S.S., Barshilia, H., Singh, R.K. Machining response and damage evolution of amorphous carbon (WC/a-C) coated tools in high-speed micromilling of Ti-6Al-4V, Journal of Micro and Nano-Manufacturing, ASME, 2020. http://dx.doi.org/10.1115/1.4046192
9. Zariatin, D.L. Investigation of the micro-milling process of thin-wall features of aluminum alloy 1100, International Journal of Advanced Manufacturing Technology, CrossMark Springers, 2018. https://link.springer.com/article/10.1007%2Fs00170-017-0514-8
10. Mario J. Remolina, Marco A. Velasco, Córdoba, E. Chip experimental analysis approach obtained by micro-end-milling in (Ti-6Al-4 V) titanium alloy and (7075) aluminium alloy, Journal of King Saud University – Engineering Sciences, 2021. https://doi.org/10.1016/j.jksues.2021.04.003
11. Walczak, M., Pasierbiewicz, K., Szala, M.

Adhesion and mechanical properties of TiAlN and AlTiN magnetron sputtered coatings deposited on the DMSL titanium alloy substrate, ACTA PHYSICA POLONICA A, 2019; 136(2). http://dx.doi.org/10.12693/APhysPolA.136.294

12. Niemczewska-Wójcik, M., Madej M. Surface topography and tribological properties of cutting tool coatings. Advances in Science and Technology Research Journal. 2023; 17(6), 39–48. https://doi.org/10.12913/22998624/173214
13. Özkan, D., Yilmaz, M.A., Karakurt, D., Szala, M., Walczak, M., Bakdemir, S.A., Türküz, C., Sulukan, E. Effect of AISI H13 steel substrate nitriding on AlCrN, ZrN, TiSiN, and TiCrN multilayer PVD coatings wear and friction behaviors at a different temperature level. Materials 2023; 16, 1594 https://doi.org/10.3390/ma16041594
14. Shingea, A.R., Dabadeb, U.A. The effect of process parameters on material removal rate and dimensional variation of channel width in micro milling of aluminium alloy 6063, Procedia Manufacturing, Elsevier, 2018. Design Engineering. 10.1016/j.promfg.2018.02.024
15. Davoodi, B., Eskandari, B. Tool wear mechanisms and multi-response optimization of tool life and volume of material removed in turning of N-155 iron–nickel-base superalloy using RSM, Measurements, Elsevier, 2015. http://dx.doi.org/10.1016/j.measurement.2015.03.006
16. Özbek, N.A. Effects of cryogenic treatment types on the performance of coated tungsten tools in the turning of AISI H11 steel, Journal of Materials Research and Technology, Elsevier, 2020. https://doi.org/10.1016/j.jmrt.2020.03.038
17. Ucun, I., Aslantasx, K., Bedir, F. The effect of minimum quantity lubrication and cryogenic pre-cooling on cutting performance in the micro milling of Inconel 718, J Engineering Manufacture, SAGE, 2015. http://dx.doi.org/10.1177/0954405414546144
18. Mokhtar, M.S.M., Yusoff, A.R. Effect of machining parameters on micro-burrs formation of aluminium puncher using high-speed machining process, Journal of Advanced Research in Applied Mechanics, SEMARAK ILMU, 2024. https://doi.org/10.37934/aram.115.1.4760
19. Mokhtar, M.S.M, Yusoff, A.R. Effect of micro-milling parameters on burr formation and surface roughness in aluminum microchannels puncher, Jurnal Tribologi, MYTRIBOS, 2024.
20. He, Q., Kang, X., Wu, X. Micro-milling of additively manufactured Al-Si-Mg aluminum alloys, Materials, MDPI, 2024. https://doi.org/10.3390/ma17112668
21. Dang, M.N., Singh, S., Navarro-Devia, J.H., King, H.J., Hocking, R.K., Wade, S.A., Stephens, G., Papageorgiou, A., & Wang, J. An investigation into the surface integrity of micro-machined high-speed steel and tungsten carbide cutting tools. Micromachines, 2023; 14(10), 1970. https://doi.org/10.3390/mi14101970
22. Biermann, D., Klocke, F., & Klink, A. Burr formation in micro milling of austenitic stainless steel. International Journal of Advanced Manufacturing Technology, 2009; 41(5–6), 497–507. https://doi.org/10.1016/j.procir.2012.07.018
23. Kowalczyk J., Madej M., Piotrowska K., Radoń-Kobus K. The impact of a movement type on tribological properties of AlTiN coating deposited on HS6-5-2C steel. Advances in Science and Technology Research Journal. 2024; 18(2), 305–316. https://doi.org/10.12913/22998624/185164
24. Li, X., Zhang, L., & Zhang, Y. Surface integrity and burr formation in micro milling of 12L14 steel under minimum quantity lubrication. Journal of Manufacturing Processes, 2019; 45, 1–10. http://dx.doi.org/10.1007/978-3-642-00568-8_15
25. Samuel, S., Sahoo, S., & Sahoo, S. Performance evaluation of TiAlN-coated WC micro-mills in micromilling of Nimonic 75 nickel alloy. Journal of Manufacturing Processes, 2020; 45, 1–10.
26. Swain, N., Venkatesh,1, V., Kumar, P., Srinivas, G., Ravishankar, S., Barshilia, H.C. An experimental investigation on the machining characteristics of Nimonic 75 using uncoated and TiAlN coated tungsten carbide micro-end mills, CIRP Journal of Manufacturing Science and Technology, https://doi.org/10.1016/j.cirpj.2016.07.005
27. Rahman, M.M., & Rahman, M.M. (2005). Performance of cryogenically treated tungsten carbide tools in milling operations. International Journal of Advanced Manufacturing Technology, 25(9–10), 1001–1005. http://dx.doi.org/10.1007/s00170-005-0379-0
28. Balázs, B.Z., Jacsó, Á., & Takács, M. Micromachining of hardened hot-work tool steel: Effects of milling strategies. The International Journal of Advanced Manufacturing Technology, 2020; 108(9–10), 2839–2854. https://doi.org/10.1007/s00170-020-05561-x
29. Hu, G., Xin, W., Zhang, M., Chen, G., Man, J., & Tian, Y. Development of a fast positioning platform with a large stroke based on a piezoelectric actuator for precision machining. Micromachines, 2024; 15(8), 1050. https://doi.org/10.3390/mi15081050
30. O'Toole, L., Kang, C.-W., & Fang, F.-Z. Precision micro-milling process: State of the art. Advances in Manufacturing, 2020; 9(4), 173–205. https://doi.org/10.1007/s40436-020-00323-0
31. Wardle, F., & Davies, M. Design of a five-axis ultra-precision micro-milling machine—UltraMill: Part 1—Holistic design approach, design considerations and specifications. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2009; 223(6), 707–718. http://

dx.doi.org/10.1007/s00170-009-2128-2

32. Kang, C.-W., O'Toole, L., & Fang, F.-Z. Precision micro-milling process: State of the art. Advances in Manufacturing, 2020; 9(4), 173–205. https://doi.org/10.1007/s40436-020-00323-0
33. Gonçalves, M.C.C., Alsters, R., Curtis, D., M'Saoubid, R., Ghadbeigia, H. Evolution of surface quality in micromilling Ti-6Al-4V alloy with increasing machined length, Procedia CIRP, Elsevier, 2024. https://doi.org/10.1016/j.procir.2024.05.040
34. Özbek, N.A. Effects of cryogenic treatment types on the performance of coated tungsten tools in the turning of AISI H11 steel, Journal of Materials Research and Technology, Elsevier, 2020. https://doi.org/10.1016/j.jmrt.2020.03.038
35. Alam, S.T., Tomal, A.N.M A., Nayeem, M.K. High-speed machining of Ti–6Al–4V: RSM-GA based optimization of surface roughness and MRR, Results in Engineering, Elsevier, 2023. https://doi.org/10.1016/j.rineng.2022.100873
36. Kundiya, R., Pawade, R., More, S., Datir, G., Kundiya, K. Acoustic emission signal correlation with micro-machining characteristics of Ti-6Al-4V alloy, International Journal on Interactive Design and Manufacturing (IJIDeM), Spingers, 2024. http://dx.doi.org/10.1007/s12008-024-01956-2
37. Dehena, S., Segebadea, E., Gerstenmeyera, M., Zangera, F., Schulzea, V. Milling parameter and tool wear dependent surface quality in micro-milling of brass, Procedia CIRP, Elsevier, 2020. 10.1016/j.procir.2020.02.024
38. Vázquez, E., Gómez, X., Ciurana, J. An experimental analysis of process parameters for the milling of micro-channels in biomaterials, Int. J. Mechatronics and Manufacturing Systems, 2012.
39. Zhang, H., Chen, L., Sun, J., Wang, W., Wang, Q. An investigation of cobalt phase structure in wc–co cemented carbides before and after deep cryogenic treatment, Int. Journal of Refractory Metals and Hard Materials, Elsevier, 2015. http://dx.doi.org/10.1016/j.ijrmhm.2015.04.007
40. Khare, S.K., Gulati, P., Singh, J.P., Phull, G.S. Effect of High-Speed Machining on Surface Roughness Characteristics Ra, Rq, RZ, E3S Web of Conferences, ICMPC 2023, 2023. http://dx.doi.org/10.1051/e3sconf/202343001271
41. Varghese, A., Kulkarni, V., Joshi, S.S. Tool life stage prediction in micro-milling from force signal analysis using machine learning methods, Journal of Manufacturing Science and Engineering, ASME, 2020. http://dx.doi.org/10.1115/1.4048636
42. Liang, Z., Gao, P., Wang, X., Li, S., Zhou, T., Xiang, J. Cutting performance of different coated micro end mills in machining of Ti-6Al-4V, Micromachines, MDPI, 2018. https://doi.org/10.3390/mi9110568
43. Kowalczyk, J., Madej, M., Piotrowska, K., Radoń-Kobus, K. The impact of a movement type on tribological properties of AlTiN coating deposited on HS6-5-2C steel. Advances in Science and Technology Research Journal. 2024; 18(2), 305–316. https://doi.org/10.12913/22998624/185164
44. Walczak, M., Pasierbiewicz, K., Szala, M. Effect of Ti6Al4V Substrate Manufacturing Technology on the Properties of PVD Nitride Coatings, 2022; 142, 6 Proceedings of the XIII International Conference on Ion Implantation and Other Applications of Ions and Electrons (ION 2022), 673–788, https://doi.org/10.12693/APhysPolA.142.723