Chapter 2

Literature review

This chapter reviews and summarizes the literature on several micro-milling process details pertinent to this research. The basics of the micro-milling operation are first described, emphasizing the differences between micro-milling and traditional milling techniques. The results of past experimental studies on the size effect and the minimum uncut chip thickness are then discussed. The importance of research on improving micro-milling performance using thin film-coated tools and minimum quantity lubrication (MQL) employing water-based nanofluids, vegetable oil-based nanofluids, and oil-water emulsions is then highlighted. The chapter ends with a concise overview of the research gap, formulation of the objective of the present study, and the approach used to accomplish it.

2.1 Machining mechanics in micromilling

Mechanical micromachining employs geometrically specified cutting edges that are kinematically similar to conventional machining. Among them, micromilling is the most flexible and versatile micromachining operation. The standard diameter variation for micro-milling endmills is 25 μm to 1000 μm [23]. However, single cutting-edge micro end mill diameters of 12.5 μm and 6 μm were also utilized by researchers [24]. Fig. 2.1 shows the differences in scale between conventional milling and micromilling tools. Table 2.1 displays the differences between micromilling and macro milling tool specifications. Small diameter micro-milling cutter needs to rotate at incredibly high speeds to accomplish even moderate processing rates. They also need a robust spindle to maintain excellent precision when cutting forces are significant. Micro-cutting, therefore, cannot be characterized as just a direct downscaling of traditional cutting because several inherent critical issues are present. The size effect plays a significant role in elaborating these issues, where the uncut chip thickness is on par with or even less than the tool edge radius. The effective rake changes to negative in many cases, as shown in Fig. 2.2, which nonlinearly increases the specific cutting energy. Furthermore, in micro-cutting, the undeformed chip thickness often follows the material grain size; therefore, the homogeneity and isotropy of the work material cannot be anticipated.

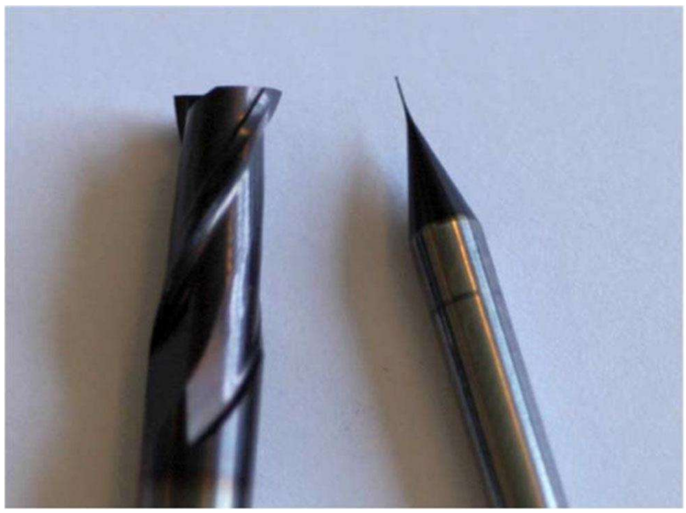

Fig. 2.1 Photographs illustrating the difference in scale between conventional milling (left) and micro-milling [25]

Table 2.1 Comparison of micro-milling and conventional macro milling cutters [26]

		Micromilling	**Macromilling**
Tool geometry requirements	Tool diameter	< 1000 μm	1-500 mm
	Cutting edge radius	0.1-10 μm	1-100 μm
Process details and material removal principles	Uncut chip thickness	0.1-50 μm	0.1-10 mm
	Tool runout	< 2 μm	< 30 μm
	Elastic recovery after machining	Yes	No
	Size effect phenomenon	Yes	No
Applications and product needs	Required machined surface roughness R_a/S_a	10-100 nm	< 12.5 μm
	Required dimension tolerance	0.1-5 μm	< 100 μm

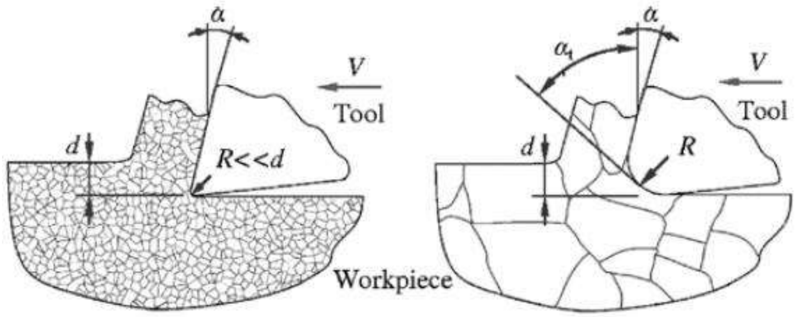

Fig. 2.2 Comparison between tool edge radius, grain size, and undeformed chip thickness in traditional milling and micromilling [27]

2.1.1 Size effect and minimum undeformed chip thickness

In micromilling, size effect originating from the low ratio of undeformed chip thickness to tool edge radius could dominate the process of metal removal and the mechanics of chip development. This size effect in micromilling is established in terms of the minimum uncut chip thickness, the specific cutting force, surface topography, and burr formation. Complete chip production is not feasible when the uncut chip thickness (h) is less than or equal to the minimum uncut chip thickness (h_{min}) shown in Figs. 2.3(a)–(b). Plowing and elastic or elastic-plastic deformation then take place. Consequently, shearing of material due to plastic deformation results in correct chip formation when the value of the uncut chip thickness is greater than the minimum undeformed chip thickness (MUCT), as illustrated in Fig. 2.3(c). Numerous researchers have examined the connection between the MUCT and edge radius and its impact on cutting forces, surface roughness, burr development, and tool wear by applying experimental, computational, and analytical techniques. A few works by them, mainly computed through experiments, are discussed.

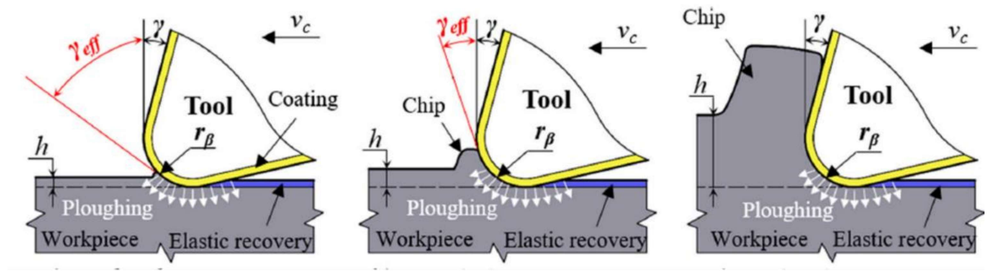

Fig. 2.3 Diagram of the processes for removing microchips in (a) elastic, (b) elastic-plastic, (c) plastic regime [8]

Aramcharoen and Mativenga [28] found minimum surface roughness when the tool edge radius is comparable to the feed per tooth. At the same time, burr formation decreased with an increase in the ratio of uncut chip thickness and tool edge radius. Oliveira et al. [29] used experimental micromilling of AISI 1045 steel to determine the MUCT using quantitative (specific cutting force and surface roughness) and qualitative (chip formation and surface topography) studies. In their work, it was indicated that irrespective of the material of the workpiece or the process used to generate h_{min}, the MUCT could be changed roughly within 1/4 and 1/3 of the cutter edge radius. Kang et al. [30] evaluated the cutting force behavior during the micromilling of AISI 1045 steel to determine the MUCT. Empirical research revealed that the MUCT should be 0.3 times the cutting edge radius. Sahoo et al. [31] found that the MUCT for the micromilling of P-20 steel varies between 0.25-0.33 r_e. They found significant enhancements in burr width, burr height, and specific cutting force with a decrease in feed per flute below the MUCT. Anand and Mathew [32] assessed the MUCT by varying feed per flute for dry and vegetable oil MQL conditions. The MUCT for micro-end milling Inconel 718 was found to be 0.3 times the tool edge radius.

When micromilling Ti6Al4V alloy, Aslantas et al. [33] addressed the tool wear phenomenon by decreasing the tool diameter and increasing the edge radius value. Additionally, they calculated the MUCT value by considering how cutting force and surface roughness varied with feed per flute. They then discovered that the MUCT value was 0.5 times the tool edge radius value.

2.1.2 Difficulties in micromachining of titanium alloys

Titanium alloys have extensive use in various industries, including biomedical, automotive, aerospace, optics, communications, precision dies, watchmaking, and electronics. This is due to their extraordinary characteristics, which include excellent corrosion resistance, high specific strength, high fatigue strength, and biocompatible nature. The leading causes of titanium's difficulty in machining are as follows: low elastic modulus, relatively high reactivity, and poor thermal conductivity. Again, because the micro end-mill has a smaller diameter than the macro end-mill, it is substantially less stiff. Therefore, even with a slight difference in cutting force, deflection of the micro end-mill occurs frequently in the case of micro-milling. Additionally, catastrophic tool failure is brought on by deflection combined with intermittent cutting mechanics. These issues are typically more problematic when cutting hard materials like superalloys based on nickel, and titanium, etc. Furthermore, due to Ti6Al4V's poor thermal conductivity and heat-building characteristics, as well as the plowing effect that is a critical part of micromachining, tools wear out quickly, produce severe burrs, and fail catastrophically. To reduce friction and the temperature of the machining zone, abrasion-resistant coated tools and coolant/lubricant are frequently employed. This reduces quick tool wear and enhances surface quality.

2.2 Process performances in micro-milling

The micro-milling operation's effectiveness is evaluated using various responses. The main factors affecting the process's success are burr formation, surface roughness, tool wear, specific cutting force, and cutting temperature. The level of quality achieved, specifically burr generation and surface roughness, is directly correlated with tool wear.

2.2.1 Burr formation

Burrs are unfavorable material protrusions that extend over the machined slots due to plastic deformation or when chips are bent at the end of a cut instead of sheared. In micromilling, the burr is a severe problem as the burr size is equal to or larger than the dimension of micro parts. Burr is undesirable and inevitable, yet it must be avoided and decreased to a reasonable level for the adequate performance of a machined component. Because of the tiny dimensions of the micro components, traditional deburring methods cannot help eliminate burrs in micromachining. Additionally, deburring might impart geometric inaccuracy or residual stress on smaller parts [34]. As the tool passes, the workpiece is subjected to abrupt impact stress, causing the engagement region to squeeze across all sides, proceeded by multiple deformation shearing regions, namely shearing, primary shear, plastic deformation, and elastic deformation regions (Fig. 2.4a). Deformation locations expand along the route of the least resistance area, i.e., elastic zones, as the tool advances in the direction of V_c (cutting velocity) until it meets the workpiece border (Fig. 2.4b). As the tool proceeds further, a negative shear zone forms, and the previous shear zone tries to connect with it (Fig. 2.4 c-d). Consequently, as seen in Fig. 2.4(e), the workpiece deforms considerably, promoting crack growth along the primary zone. At last, the fractures appear above the primary shear zone, and burrs remain at the corners.

Three mechanisms are responsible for burr formation: lateral deformation, chip bending, and chip tearing. They are classified according to the mechanism into Poisson, rollover, tear, and cut-off burrs and are defined as follows (Fig. 2.5):

1) Poisson burr: The Poisson burr is caused by the lateral movement of stagnant materials just underneath the cutting edge radius.
2) Rollover burr: The rollover burr consists of a bent chip instead of a sheared chip, as a consequence of which a considerable burr is formed.
3) Tear burr: The tear burr is caused by material getting loose from the surface instead of shearing away. It resembles a burr generated during a punching procedure.
4) Cut-off burr: Material left behind whenever the workpiece slips from stock before the cutting has separated.

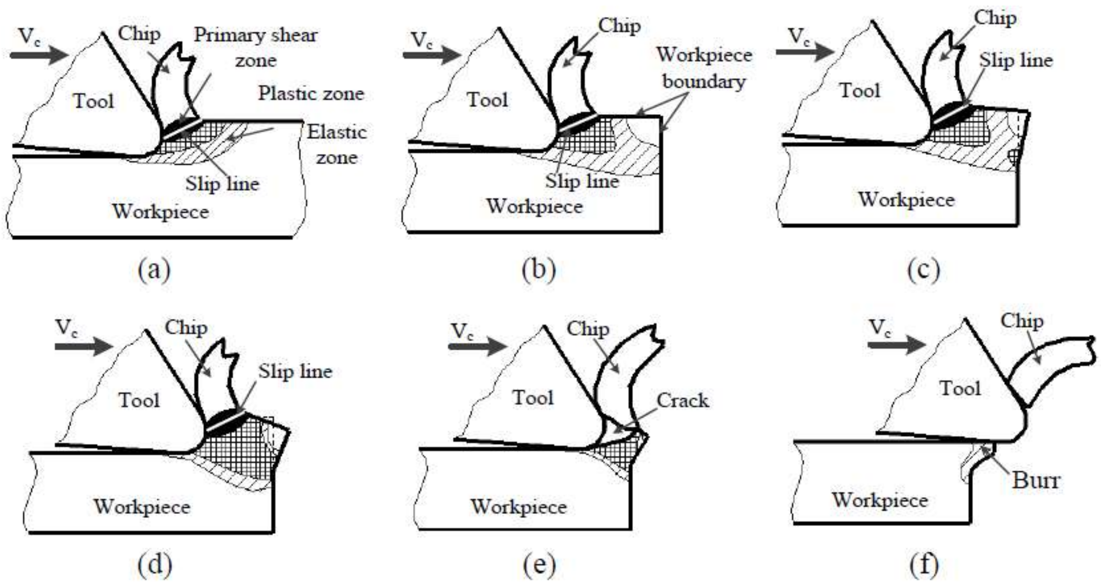

Fig. 2.4 Stages of top burr formation: Initiation, propagation, and formation [35]

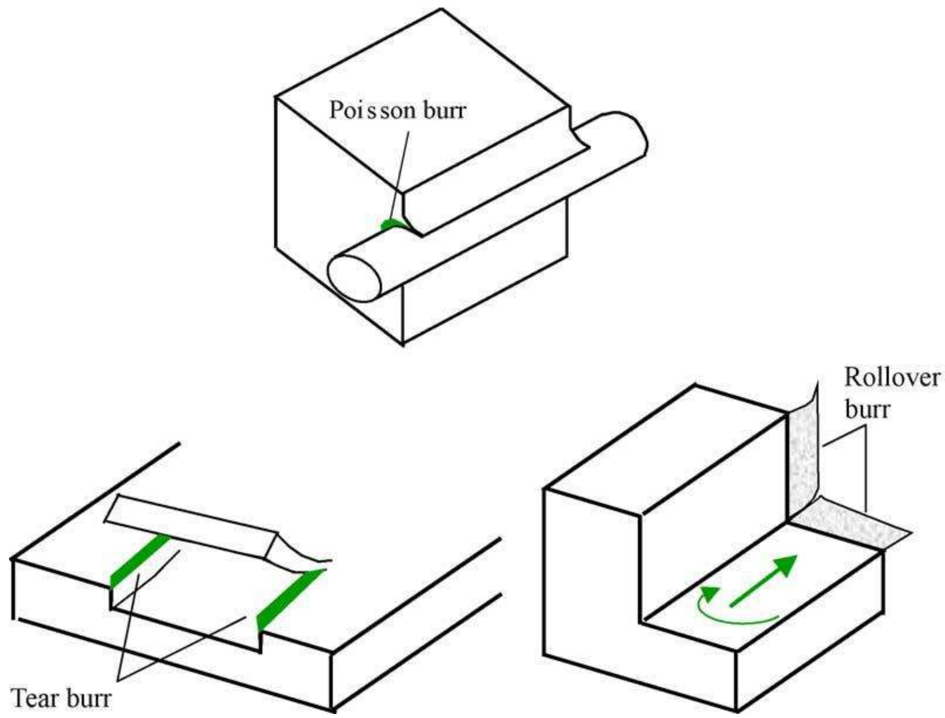

Fig. 2.5 Diagram of Poisson burr, tear burr, and rollover burr [36]

Burrs can be categorized into eight types according to where they develop in total immersion slot milling, as illustrated in Fig. 2.6. Five types are considered relevant for assessment: entrance side burrs on the down-milling side, top burrs from up and down milling, exit burrs at the bottom of the slot, and lastly, exit side burrs on the up milling side. Top burrs in up and down milling are very difficult to eradicate. Chern [37] found five different types of burr during face milling of aluminum alloys such as knife-type, wave-type burr, curl-type, edge breakout, and secondary burr, as shown in Fig. 2.7. Various deburring techniques are used to reduce and control burr formation, such as electrochemical polishing, micro-EDM, ultrasonic cavitation based deburring, and micro-peening [38-41]. Saptaji et al. [42] tried to minimize the burr formation in micromilling by providing a side edge angle to the workpiece and a taper tool angle. They found that the largest value of both angles minimized burr formation. The application of coated tools and coolants/lubricants also reduces burr formation as it is directly related to tool wear. Jackson et al. [43] found that the TiAlN coating reduces burr formation by maintaining cutting edges intact for an extended period. Danish et al. [44] investigated the use of MQL/Flood conditions in the micromilling of Inconel 718 and discovered considerable benefits for large burr prevention. Burr inhibitions are also obtained using the assistance of vibration micromilling and laser micromilling [45, 46]. Zheng et al. [47] used vibration to aid in micromilling to reduce burrs and discovered that burr height decreased as vibration frequency increased.

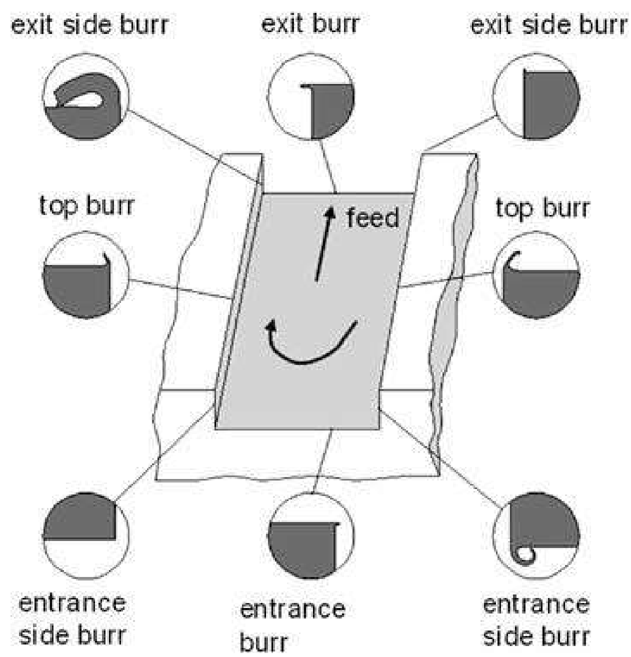

Fig. 2.6 Types of milling burr according to locations [48]

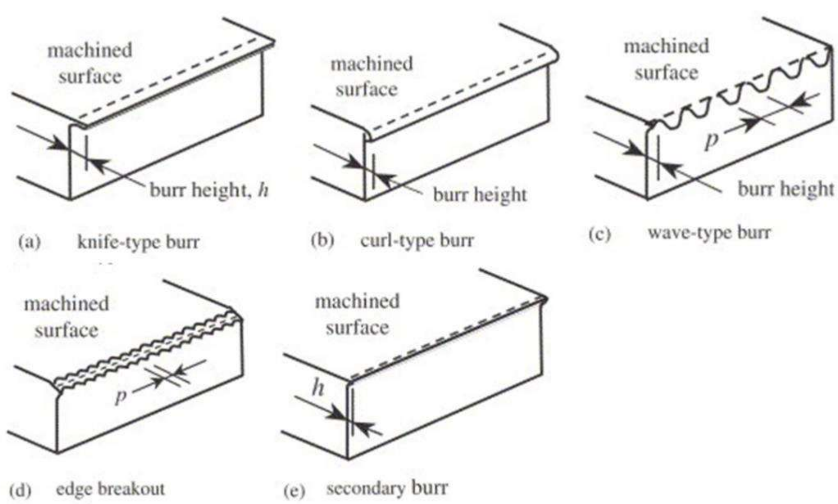

Fig. 2.7. Five types of burrs in face milling [37]

2.2.2 Tool wear

Tool wear evaluations in machining often refer to the procedures outlined in standards like ISO8688-1 and ISO8688-2. Unfortunately, the ISO standards appear inappropriate for micro-milling, necessitating average flank wear and maximum flank wear values of 0.3 mm and 0.6 mm, even higher than the dimension of the micro part. Accelerated tool wear is a severe issue in micro end-milling; yet, while tool wear is unwanted, tool fracture appears to be a more significant issue. Small micro end-mills may break if the chip jams or the cutting edges become worn. The most prevalent criteria for measuring tool wear include edge radius enlargement, flank wear, and tool diameter reduction, as shown in Figs. 2.8 (a)-(c). Microgroove width has occasionally been used to estimate tool wear. Tool wear is also assessed using a scanning electron microscope and energy-dispersive spectroscopy instruments, which can show adhesion, abrasion, built-up edge, and oxidation wear on the rake, flank surfaces, and cutting edges. It is very challenging to determine the exact geometry of the used tools due to their tiny size. The percentage of diameter reductions was defined as:

$$\%\ \text{diameter reduction of tool} = \frac{D_O - D_{worn}}{D_O} \tag{2.1}$$

Where D_o and D_{worn} are the diameters of the new and used tools, respectively.

2.2.3 Surface roughness

A surface's quality can be determined by its surface roughness. It is a geometric occurrence that represents the amount of irregularity that can be produced as a result of machining. The measure of surface roughness is influenced by the tool's sharpness and how much burnishing or rubbing happens as a result of the plowing action. Surface roughness was utilized to evaluate how well the groove surface made by the micro milling procedure was operating.

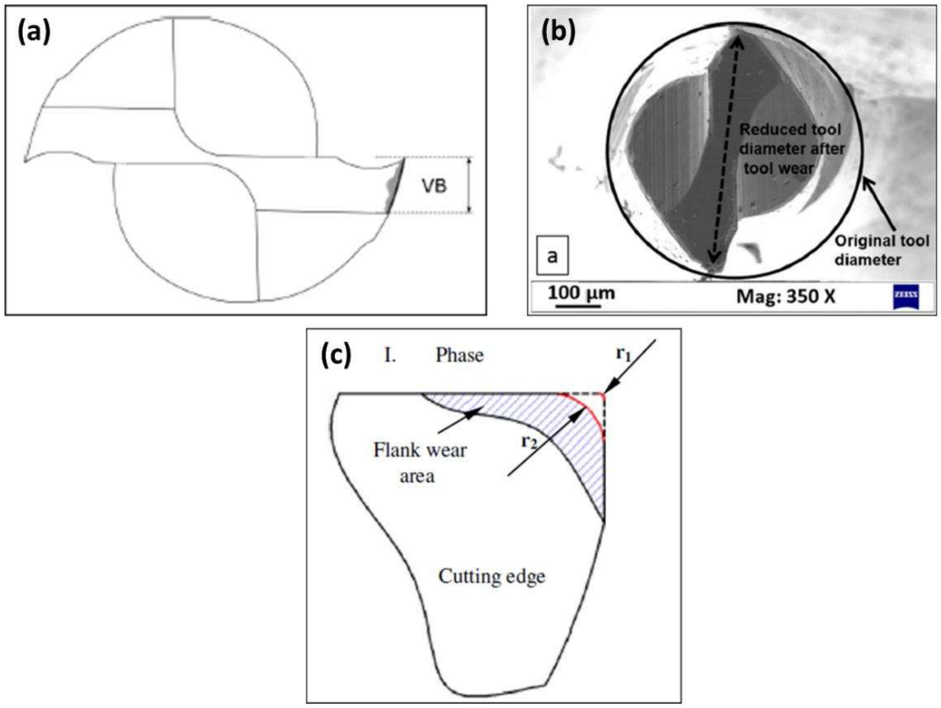

Fig. 2.8 Measurement of (a) flank wear [49], (b) tool diameter reduction [31], and (c) change in edge radius [50]

It is evident that the micro-end milled ground has regions that are both plowing and shearing prominent. The 2D surface roughness metrics could not adequately describe the micro end-milling workpiece surface smoothness. As a result, the measure for areal surface roughness, known as the arithmetic average height of an area (S_a), was mainly preferred. There are several factors, such as MUCT, size effect, tool deflection, tool wear, built-up edge, and material properties, that affect surface roughness.

2.2.4 Cutting forces

Tool wear progression is related to cutting forces, and the magnitude of cutting forces shows the actual state of machining. Cutting forces in micromilling differ from traditional milling due to various factors such as vibrations, high spindle speed, tool run-out, and minimum uncut chip thickness effect. It's challenging to get a precise tool wear picture in the machining operation because the rotational speed is so high and the size of the micro-milling tool is so tiny. Indirect tool wear assessments are possible using cutting forces without interrupting the machine, enabling tool wear monitoring in real-time [51]. Fig. 2.9 shows the schematic of micro-milling force at the Full immersion milling. The force along the feed direction of the milling cutter is called feed force (F_x), whereas the force transverse to the feed direction is called cross-feed force (F_y). Micro-milling force is typically expressed as an average, root mean square (RMS), and peak-valley (P-V) value. The P-V value force denotes the peak valley difference of cutting force in each revolution.

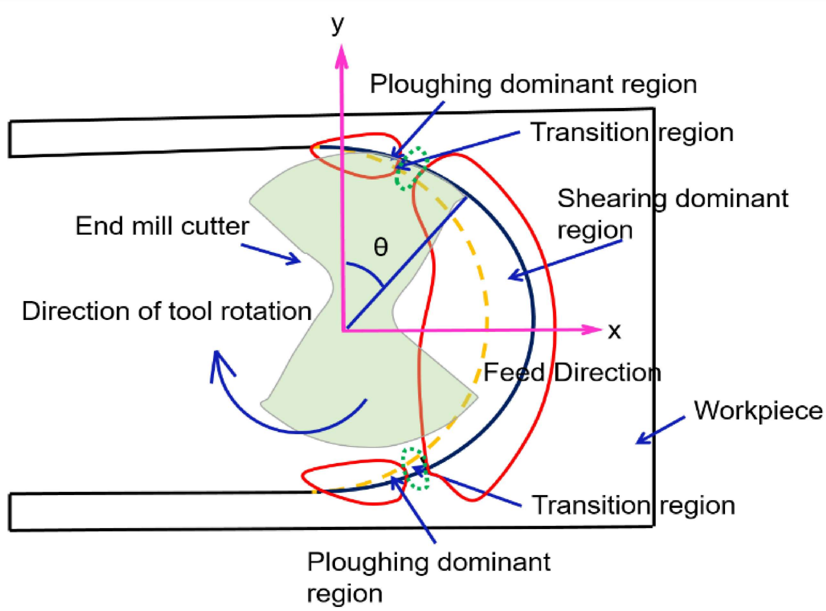

Fig. 2.9 The schematic of micromilling force in complete immersion milling [52]

2.2.5 Cutting temperature

The temperatures at the interfaces between the tool, chip, and workpiece considerably impact the machined surface's sheer quality and the severity of tool life. Due to the significantly smaller uncut chip thickness values than conventional milling, micromilling is anticipated to have considerably lower temperature readings [53]. However, the produced product may not be accurate if thermal expansion occurs during manufacturing. Due to the narrow cutting zone, temperature measurement in the micromilling operation may be challenging. Because thin-film temperature sensors are challenging to place in the cutting area and accurately acquire information, infrared thermography is constrained by the challenges of concentrating on such tiny cutting zone regions [54]. The cutting edge temperature is often 3-fold more significant than the workpiece temperature during the micro milling operation, as seen by Chen et al. [55] utilizing FEM analysis. Depending on such, cemented carbide micro-cutting tools should get special attention while operating with strong alloys since the cutting zone temperature may be higher than the maximum operating temperatures (800–1000° C) [56].

2.3 Effect of the thin film-coated tool in micromachining

A coating is an outer film deposited on a substrate to provide improved hardness, wear resistance, and protection from environmental contaminants. The attributes that can be enhanced comprise appearance, wettability, abrasion resistance, wear resistance, chemical stability, friction coefficient, and heat barrier capacity. The biggest issue with this approach is that the thin coatings significantly alter the already-minuscule tool size, which might potentially alter the cutting edge radius. Generally, a physical vapor deposited layer (PVD) is preferred over chemical vapor deposition (CVD) due to the lower deposition temperature that preserves toughness and fine grain size and achieves lower thin coating thickness up to 5 µm. The exceptional hardness, wear resistance, low frictional coefficient, and chemical inertness make diamond coating suitable for micro-tools. However, adhesion between diamond film and substrates is inferior and easily peeled off, and high diffusion wear also causes it not to be beneficial for machining ferrous alloys [57]. Therefore, coatings have often been deposited over cemented carbide micro tools to reduce tool wear and enhance cutting capabilities. In general, metal and diamond coatings are the two main types found on micromachining tools. TiN, CrN, AlCrN, AlTiN, and TiAlN constitute the most prominent categories of metal coatings. TiN and CrN-coated microtools were initially used in micromilling. However, it delaminated rapidly due to its lower hardness. Hence, aluminium was added to TiN and CrN coatings, like AlCrN, AlTiN, and TiAlN coatings, to increase the thin film hardness. According to this, many investigators have worked on studying how well thin-film coated tools work in micro milling compared to uncoated tools, and a few of these immense contributions are mentioned below.

Ozel et al. [58] utilized uncoated and cBN-coated WC micro end-mills with different cutting tool diameters and parameters to investigate the effect on surface roughness, burr formation, and tool wear rate. They also predicted cutting temperatures using FEM modeling. Due to a reduced coefficient of friction and higher thermal conductivity, cBN-coated tools dramatically reduce burr formation and improve surface smoothness. Wu and Cheng [59] found that diamond-like carbon (DLC) coating reduces cutting forces, tool wear, adhesion of material on the tool, surface roughness, and burr formation in the micromilling of Al6061-T6. However, the application of cutting fluid with an uncoated WC tool was more influential than DLC coated tool. In another study, the same research team discovered that nano-crystalline diamond (NCD) coating reduces cutting forces and tool flank wear by 16% and 25%, respectively [60]. Kumar et al. [61] investigated the effect of different coatings on tool wear mechanisms with and without laser support in the micromilling of hardened steel. Using SEM and EDS analyses, coating delamination wear was discovered to be the primary wear mechanism. In their investigations on the micro-milling of austenitic stainless steel X5CrNi18-10, Biermann [62] et al. observed that introducing Al to CrN and TiN coatings produced favorable outcomes in terms of tool wear due to an increase in hardness and a decrease in reactivity towards work material due to the formation of alumina oxide. They also noticed that spalling or cutting-edge chipping did not occur during machining. Ucun et al. [50] observed a significant reduction in tool wear and built-up edge formation using single-layer AlCrN, AlTiN, DLC coating, and multilayer TiAlN + AlCrN, TiAlN +WC/C coating than uncoated WC micro mill for micromilling of Inconel 718 alloy. They also utilized the MQL process with AlCrN coated WC micro-mill and found a significant reduction in tool wear and material adhesion using the MQL technique. In another investigation, the same authors analyzed the effect of tool wear and built-up edges on surface roughness [63]. They found lower surface roughness obtained with DLC, AlTiN, and TiAlN +WC/C coatings. At the same time, AlCrN and TiAlN + AlCrN depicted rougher surfaces owing to the chemical affinity of CrN coating with Inconel 718 and built-up edge formation on the tool that further smeared on machined surfaces. Figs. 2.10-2.12 demonstrate the effect of built-up edge on tool and surface roughness of machined microchannel. Muhammad et al. [64] utilized different tool coatings and parameters optimization for reduction of burr and surface roughness in micromilling of Inconel 718. They found that cutting velocity and depth of cut were more influential for surface roughness and top burr width. At the same time, the AlTiN coating was more effective in burr reduction owing to the lower cutting edge radius. For micro-milling Ti-6Al-4V alloy, Aslantas et al. [33] investigated the effects of several coating materials, including the NCD, AlTiN, and AlCrN. They observed surface roughness, cutting forces, and tool wear variation with machining length with various types of tools. Cutting forces increased with machining length owing to tool wear; however, surface roughness first decreased and then increased due to the transition between feed rate and cutting edge radius. NCD-coated tools performed poorly for cutting forces, tool wear, edge chipping, and surface roughness among coated tools. Lu et al. [65] analyzed the tool wear and its mechanism in the micromilling of Inconel 718 at different machining times. The main wear patterns observed were flank wear, chipping, coating delamination, diffusion, and oxidation wear.

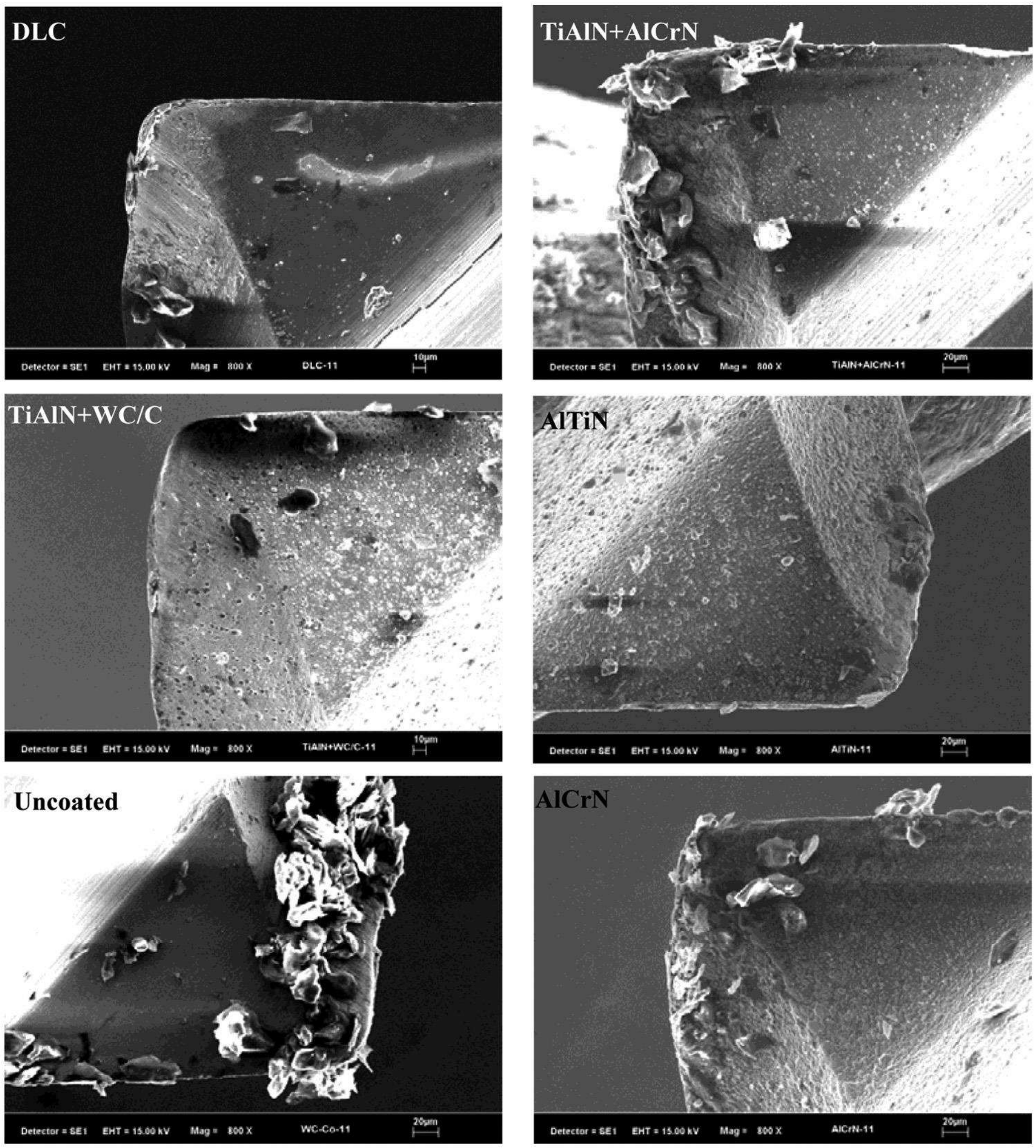

Fig. 2.10 SEM images of chips adhering to the cutting edges of coated tools [66]

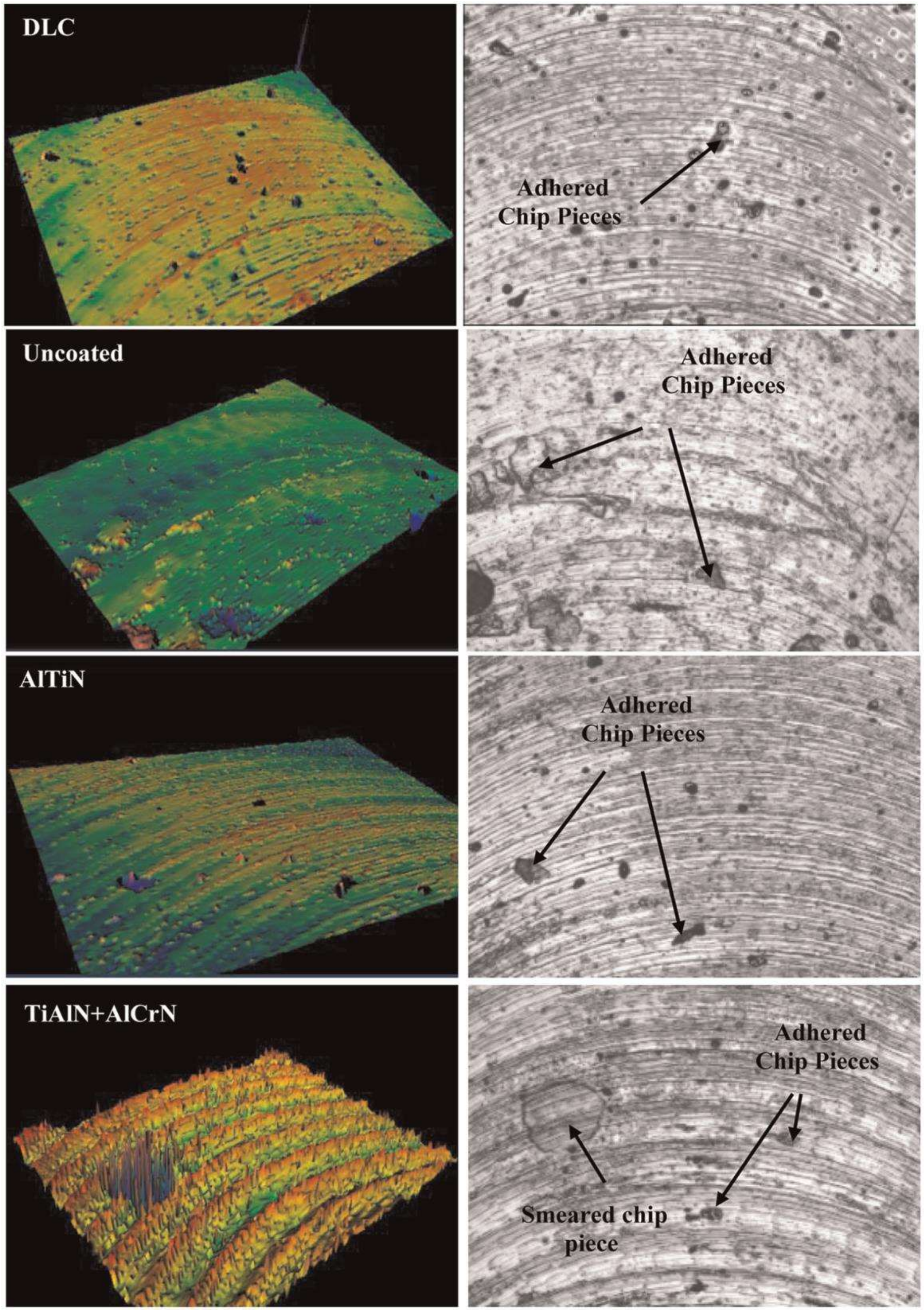

Fig. 2.11 Three-dimensional topographic images of surfaces machined by uncoated, DLC, AlTiN, and TiAlN + AlCrN coated micro mills [66]

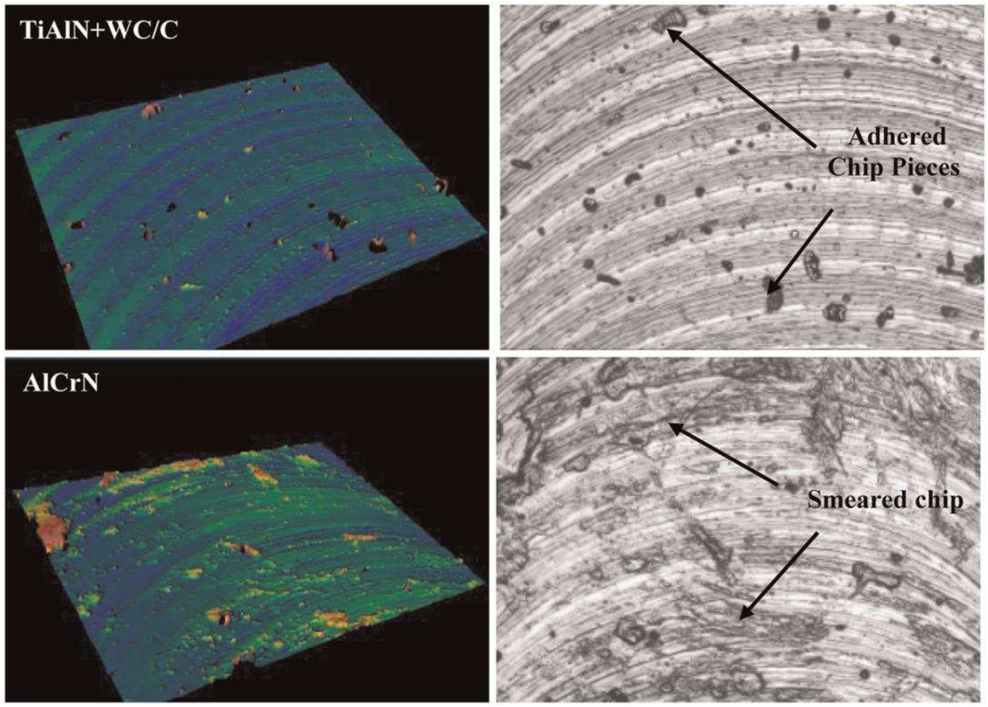

Fig. 2.12 Three-dimensional topographic images of surfaces machined by TiAlN + WC/C and AlCrN coated micro mills [66]

2.4 Metal cutting fluids (MCFs) and sustainable techniques

Cutting fluids extract heat, lubricate the machining zone, prevent corrosion, and flush the chip away from machining zone [67]. Cutting fluid helps considerably enhance machining performance, such as tool wear, cutting forces, burr formation, and surface roughness. Machined surface finish has become increasingly critical as micromachining and ultra-precision manufacturing have developed and been used to machine difficult-to-machine materials. According to reports, mineral-based oils account for over 85% of coolants used worldwide in manufacturing industries. However, mineral oils and associated additives significantly impact human health and the environment, as shown in Fig. 2.13. Airborne particles and aerosols float in the air while machining, causing lung and skin ailments such as respiratory deficiency, bronchitis, and asthma [68]. Fig. 2.13 shows different health hazards related to mineral oils. Therefore, several eco-friendly lubricating/cooling solutions have been reported to address such difficulties. Dry machining, minimal quantity lubrication (MQL), minimal quantity cooling lubrication (MQCL), nanofluids MQL, biodegradable vegetable oils MQL, cryogenic lubrication, and high-pressure cooling (HPC) are some examples of such environmentally friendly cooling/lubricating solutions in cutting [69]. Dry machining that does not employ any lubricating oil could eliminate pollution problems. However, the high deformation zone temperature will quickly cause damaged tools and poor surface quality. Typically, biodegradable vegetable oil-based MCFs choose techniques that emphasize adequate lubrication and heat dissipation. Water-based MCFs, contrary to the previous criterion, are significantly favored for effective heat dissipation when lubrication is not a primary need. An oil-water emulsion provides both cooling and lubrication. MQL-based lubricants decrease cutting liquid waste while using biodegradable oil, deionized water, and vegetable oil water emulsions with the MQL system promotes sustainability. The MQL method includes spraying or atomizing a tiny portion of lubricating oil in a compressed air stream focused into the cutting zone, typically at a flow rate between 50 and 500 ml/h [70]. Internal and external mist supply systems were distinguished as the two different types of MQL systems. In the internal MQL system, mist is supplied through a channel or through a hole inside the tool, while in the external MQL system, mist is supplied by a nozzle at a particular distance and nozzle angle. Because of the small tool diameter, an external MQL system is employed in micromilling. An internal MQL system is not feasible. The thermophysical properties of nanofluids, such as thermal conductivity, viscosity, wettability, and heat transmission capacity, are enhanced by further applying them using MQL. A comparatively new category of fluids called nanofluids comprises a base fluid contained within nanoscale (1-100 nm) particles [71]. These typically metallic, metal oxide, CNT, graphene, and molybdenum dioxide solid particles improve the lubricating and cooling properties of the base fluid. The base fluids are water, mineral oil, vegetable oil, and ethylene glycol. The characteristics of nanofluids are influenced by various features, including the kind of nanoparticles, their dimension and shape, their volume/weight percentage, the type of working fluids, the fluid's PH level, temperature, and the duration of the sonication.

Fig. 2.13 Health hazards related to the use of minerals oils [72]

Two different approaches have been used to create nanofluids. One involves a single step, while the second involves two step method. Due to its lower cost and ease of formation, the two-step approach is the most commonly employed in industry to create nanofluids. However, the fundamental concern with the two-step technique is the stability of nanofluids, which may be obtained by magnetic force agitation, ultrasonic agitation, and homogenizing. A different cutting fluid is called hybrid nanofluids, which comprise two or even more nanoparticles combined in the base fluid [73].

2.4.1 Lubrication mechanism of nanoparticles as lubricant additives

Various lubrication mechanisms were observed in the dispersion of nanoparticles, as illustrated in Fig. 2.14. Rolling, polishing, self-repairing or mending, and protective film were some of the mechanisms found in the literature. The spherical nanoparticles that comprise the rolling effect mechanism roll in between contact regions, transforming pure sliding friction into rolling friction. Smaller, rounder nanoparticles could improve the effectiveness of nanofluids under intense stress and their capacity to hold more load. Self-repairing or mending mechanisms fill surface grooves and balance mass loss. It also reduces the asperities contact and surface roughness. In the polishing mechanism, hard nanoparticles might operate like a polishing tool to lessen the surface roughness of contacting surfaces because of their abrasion resistance. Tribo-film formation may develop due to the deposition of nanoparticles over the surface and adsorption on moving parts. The spherical nanoparticles and layered nanosheet exfoliation also help stabilize tribofilm formation. The machining and lubrication mechanisms of different nanoparticles are described in Table 2.2.

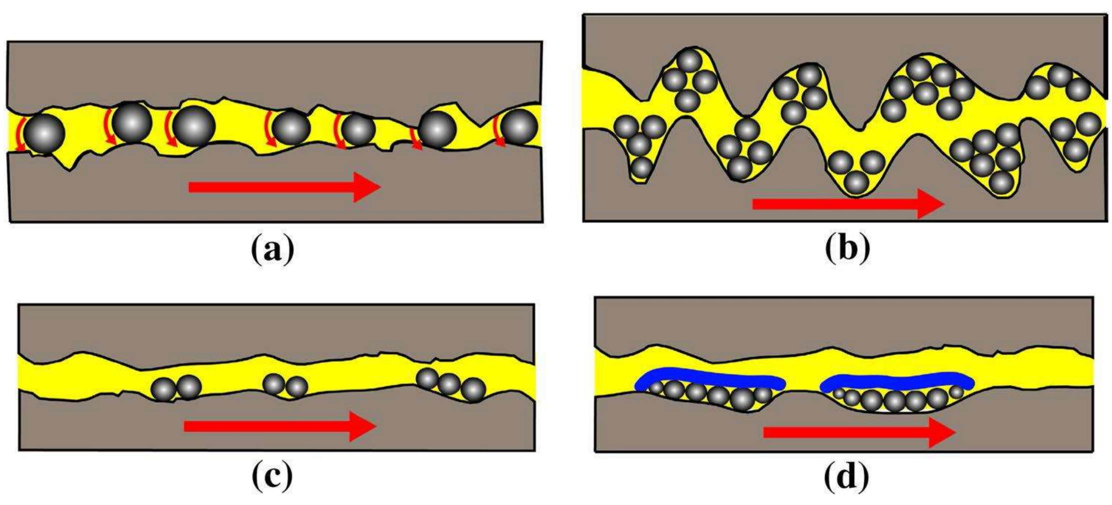

Fig. 2.14 Schematic illustration of (a) rolling, (b) self-repairing or mending, (c) polishing, and (d) tribo-film formation mechanisms [74]

2.4.2 Utilization of cutting fluids and nanofluids in micromachining with MQL

There is a massive implementation of MQL in the conventional milling process, and it is highly efficient for the improvement of machining performance. However, limited investigations are mentioned on MQL in micromilling and size effect. Prakash et al. [75] first examined how MQL affected tool wear and chip formation when micromilling pure copper. They discovered that the cutting speed reduction and feed rate increase prolonged tool life.

Table 2.2 Overview of the lubrication mechanism of nanoparticles [74]

Nanoparticles	Lubrication mechanism
Graphene	Development of protective film
MWCNT	Deposition of MWCNTs on the worn surface
Diamond	Nanoparticles plow on the worn surface and act as a polishing agent
Al_2O_3 and TiO_2	Third body rolling effect: change from sliding to rolling Formation of the lubricating film
CuO and ZnO	Nanoparticles acting as the rolling medium film formation
MoS_2	Shear deformation of nanoparticles Formation of tribo-film
WS_2	Exfoliation and squashed of nanoparticles
SiO_2	Shearing of nanoparticles, particle filling, and polishing effect
Cu	Nanoparticles fill scars and grooves
CeO_2	Third body rolling effect
PTFE	Formation of tribo-films

Canola cooking oil-water emulsion was used as cutting fluid by Burton et al. [76] in the micromilling of aluminum and steel plates. Emulsions were made through ultrasonic atomization systems to prevent the use of any surfactant. Reduction in peak-to-valley cutting forces and thinner chips obtained using vegetable oil-water emulsion compared to conventional cutting fluid. To investigate the impacts on burr formation, tool wear, and the geometry accuracy of microchannels, Vazquez et al. [77] used dry, jet, and MQL applications in the micro-milling of Ti-6Al-4V alloy. They discovered that the amount of tool wear and surface roughness was three times larger in the case of jet lubrication than in MQL application along the feed direction. In addition, the microchannel geometry was rectangular for the MQL condition and trapezoidal for the jet application. In a further study, CFD analysis showed that the jet deployment, in the circumstances of the microscale flow, resulted in a chaotic stream with higher amounts of entropy and hindered the flow from achieving the intended goal [78]. According to Li et al. [79], vegetable oil-based MQL (Bluebe Lubricants LB-1) considerably decreased tool flank wear, surface roughness, and burr formation compared to dry conditions in the micromilling of SKD 61 plates of steel. It was found that low speed and high feed rates are best suited in dry conditions. Additionally, they found that a low cobalt content is better for reducing tool wear. They experimented with various oil flow rates and air flow rates and discovered that the oil flow rate change had no impact; however, a higher air flow rate minimized tool wear.

Compared to dry micro-milling of 316L steel, Kajaria et al. [80] reported that MQL with CL 2210 EP, a commercial biodegradable oil, extended the tool life up to tenfold. Pham et al. [81] assessed the effectiveness of ionic liquids as lubricants during the micro-milling of Al 5052. They found that using a high-viscosity ionic lubricant produced a comparatively better surface finish and demonstrated extraordinarily low volatility than traditional oils or distilled water. Zhang and Jun [82] dissolved lignin, a natural additive in 5% conventional cutting fluid emulsion at different concentrations for the micromilling of Al6061. A quantity of 0.015% is the perfect amount to employ lignin as an ingredient. Chanes de Souza et al. [83] used two types of sunflower vegetable oil, one with high oleic acid content and another with a mid-oleic acid content, and compared the results with conventional emulsion. Compared to low oleic fatty acid sunflower oil and its emulsions, high oleic fatty acid sunflower oil exhibits high lubricating performance, reduced cutting forces, and superior surface finish. Nevertheless, emulsions displayed less flank wear. In micromilling of Inconel 718, sunflower oil MQL condition compared to a dry environment, 25% decline in edge radius, 30% reduction in flank wear, and 36% reduction in cutting force were noted. Additionally, using MQL led to a 7% improvement in microhardness, having smoother surfaces, along with a decrease in microcracks, prows, and flaws on the machined parts [84].

Marcon et al. [15] first implemented nanofluids lubrication in the micromachining area. In the micro-milling of H13 tool steel, they used distilled water mixed with graphite nanoplatelets as the cutting fluid. They studied how platelet size, nanoparticle concentration, and coolant flow rates affected microchannel depth, cutting forces, tool wear, and surface smoothness. Lee et al. [85] utilized 30 nm and 150 nm nano-diamond particles in paraffin oil MQL at 2 and 4 vol% concentrations in the micro grinding of steel. They revealed that 30 nm diamond nanoparticles lowered the surface finish of the workpiece by 64% while nanofluids MQL reduced normal and tangential forces by 33.2% and 30.3%, respectively. This occurs due to the spherical nano-diamond particles' high heat dissipation and ball-bearing properties. Samuel et al. [86] implemented graphene platelets (GPL) of 0.1, 0.2, and 0.5 wt%, single-wall carbon nanotubes (SWCNT), and multi-wall carbon nanotubes (MWCNT) of 0.5 wt% in semi-synthetic cutting fluid Castrol Clear-edge 6519 at 12.5% in the micro turning of 1018 steel. The movement of the graphene layers inside this platelet provides efficient lubrication and reduces cutting force. It was also observed that wetting ability, thermal conductivity, and kinematic viscosity enhanced with an increase in weight percentages of nanoparticles. In another investigation, GPL was added to canola oil at 0.05, 0.1, and 0.15 wt% concentration and enhanced thermal conductivity and kinematic viscosity with an increase in wt%. GPL-loaded canola oil has the advantage of achieving lower cutting forces. However, there is a slight increase in cutting force and surface roughness obtained using higher weight concentration owing to undispersed clumps of GPL [87].

A nanofluid MQL strategy was used by Nam et al. [88] throughout the micro-drilling procedure. In their experiment, nano-diamond particles were utilized at concentrations of 1 and 2 vol% in paraffin oil and vegetable oil. For lowering torques and thrust forces in the case of paraffin oil, 1 vol% of nano-diamond particles was superior to 2 vol% of them. On the other hand, more considerable reductions were seen in the vegetable oil example when the nano-diamond particle concentration was 2 vol%. According to Garg et al. [89], the concentration of nanoparticles in the base fluid significantly affected the torque and power needed in the MQL micro-drilling method. In the micromilling of $Ti_4Al_4Mo_2Sn$, Nithiyanandam et al. [90] studied the effect of MQL in Al_2O_3 water-based nanofluids at 1.5, 3, and 4 vol% concentrations. They concluded that 4.5 vol% is the optimal concentration for reducing surface roughness, cutting forces, and tool wear. They also found that PH value has a significant role in nanofluid stability.

Table 2.3 Influence of various cutting fluids and nanofluids in micromachining

Process	**Cutting fluids/nanofluids**	**Workpiece material**	**Outcomes**
			Cutting force, burr formation,

Micromilling	Canola oil emulsion and 5% TRIM oil emulsion	Al6061 and Steel1018	and tool wear reduced and thinner chip obtained in canola oil emulsion than 5% TRIM oil emulsion
Micromilling	Vegetable oil (MAK KIT10 ES-AL) emulsion	Ti-6Al-4V	Tool wear and surface roughness were reduced with the cooling nozzle in the feed direction
Micromilling	Bluebe Lubricants LB-1	SKD 61 steel	Tool flank wear and surface roughness with cutting length reduced in MQL condition than dry machining
Micromilling	CL 2210 EP	316L Steel	Tool life increased up to tenfold in MQL
Micromilling	(EMIM[TFSI]), distilled water (BMIM[I]), two conventional oil	Al 5052	[BMIM][I] provided the best surface quality with the lowest roughness
Micromilling	5% conventional cutting fluid emulsion + lignin additive	Al 6061	A concentration of 0.015% lignin contributed to lower peak-to-valley resultant cutting force and burr formation
Micromilling	Sunflower oil with high oleic and mid oleic acid and its emulsions	7050-T7451 Al	High oleic acid content reduced cutting forces and surface roughness, while its emulsion depicts lower flank wear
Micromilling	Sunflower oil	Inconel 718	Sunflower oil MQL reduced cutting edge radius, cutting force, and flank wear by 25, 36 and 30% compared to dry condition
Micromilling	distilled water + graphite nanoplatelets	H13 tool steel	Cutting force was reduced while the surface finish and tool state deteriorated
Micro grinding	Paraffin oil + nano-diamond particles	SK-41C tool	Lower-size spherical nanoparticles improved the

		steel	surface finish
Micro turning	Castrol clear-edge 6519 + GPL	1018 steel	Cutting force and cutting temperature reduce with nanofluids. It also enhanced wettability, thermal conductivity, and viscosity.
Micro turning	Canola oil +GPL	1018 steel	The inclusion of GPL caused cutting force, temperature, and surface roughness reduction.
Micro drilling	Paraffin oil, vegetable oil + nano-diamond	Al 6061	1 vol% and 2 vol% of nano-diamond particles in paraffin oil and vegetable oil, respectively, demonstrated better results for torque and thrust force reduction
Micro drilling	Vegetable oil	Aluminum	At nanofluid volume concentration values of 1.4 and 4, the minimum values of torque and thrust forces are achieved, respectively
Micro milling	Water + Al_2O_3	Ti4Al4Mo2Sn	At nanofluid concentration values of 4 wt%, tool wear and surface roughness were lower

2.5 Influence of MQL parameters on machining performances

The aerosol or mist formation quality determines the efficacy of MQL in the manufacturing domain. Mist formation is significantly influenced by droplet quality, which is controlled by choosing suitable MQL parameters. Several MQL parameters, such as MQL flow rate, pressure, droplet size, mixing ratio, nozzle angle, etc., significantly affect the machining performance. Mia et al. [91] used varied oil MQL flow rates of 100, 150, and 200 ml/h for milling AISI steel. Using an approach based on the Grey-Taguchi relation, they revealed that a flow rate of 150 ml/h gives the lowest cutting force and surface roughness. Ji et al. [92] found that cutting force decreases with the MQL flow rate. Although when the flow rate reaches a specific value, no further reduction in cutting force occurs. Hence, once it reaches an effective amount of cutting fluid that fills the asperities between tool and workpiece, extra lubricant does not provide fruitful results because the maximum effective flow rate, an essential for MQL-assisted machining, is dependent on viscosity, workpiece-tool interfaces, and work surface polish in addition to MQL flow rates. A greater MQL flow rate enhances the wettable surface and the number of droplets per second for AISI 52100 grinding operations, albeit it does affect the mean droplet diameter with flow rate variation [93]. Burton et al. [76] mixed canola oil in water by volume from 1-30% through ultrasonic atomization and found that mixing ratio does not change the performance of emulsions. Further canola oil-water emulsion and 5% trim solution (conventional cutting fluid) were used in micromilling of Al6061 and steel 1018. Less resultant cutting force and burr formation were observed using canola oil-water emulsion. Mishra et al. [94] revealed that low air pressure and a higher flow rate produce large droplets owing to droplets' coalescence. They select a 150 ml/h flow rate and 6 bar pressure for MQL and nanofluid MQL. Huang et al. [95] optimized nozzle distance, flow rate, air pressure, and nozzle angle in micromilling of SKD11 steel for minimum cutting force and cutting temperature. They found the best optimal parameters are nozzle distance of 40 mm, flow rate of 35 ml/h, air pressure of 3 bar and nozzle angle of 270^{o} for minimum cutting force. They found the best optimal parameters are nozzle distance of 40 mm, flow rate of 35 ml/h, air pressure of 3 bar and nozzle angle of 180^{o} for minimum cutting temperature.

2.6 Gaps in knowledge and need for research

The existing literature suggests that using various coated WC tools and eco-friendly cooling/lubrication systems can improve manufacturing sustainability. As an outcome, it is believed that applying both nanofluids MQL and coated tools together can enhance the micro-machinability even more, but no related studies have been reported in the literature. Although thin-film coated tools and water-based nanofluids MQL have been reported on a large scale for conventional machining of Ti-6Al-4V alloy, very few investigations have been carried out for the micromilling of Ti-6Al-4V alloy. Besides, the hybridization of deionized water/nano lubricant-based MQL and thin-film coated tools in micromilling of Ti-6Al-4V alloy is not reported in the published literature. Furthermore, very little research has been done on machining characteristics, particularly microscale cutting, which is appropriate for using atomically thin MoS_2 additives in vegetable oil. The present study aims to examine the relationship between variations in spindle speed and the application of different MQL flow rates of vegetable oil-water and paraffin oil-water emulsions, as well as the impact on top-burr formation and surface topography during sustained micro-milling of Ti-6Al-4V alloy.