Chapter 1

Introduction

This section provides a concise introduction to the fundamentals of micromilling, the background of the field, and the difficulties that motivate research on the machinability of superalloys, focusing on ways to improve it. Additionally, it addresses this thesis's scope, structure, and objectives.

1.1 Micro-milling background

Micromanufacturing has gained popularity in the 21st century due to the growing demand for precise micro equipment, particularly in microfluidic devices, microelectronics, healthcare, aviation, transportation, and optics, among many other fields [1]. As per Yole Development (BioMEMS report 2020), the micro-system technologies sector for healthcare devices would increase from $3.7 billion in 2019 to $6.3 billion in 2025, mainly for biomedicine. Numerous advantages of miniaturized items include their great flexibility and portability, increased functionality and accessibility, and reduced energy usage. Several conventional and non-conventional manufacturing procedures, including focused ion beam (FIB), wire electrical discharge machining (WEDM), lithography-electroplating-molding (LIGA), and pulse laser ablation (PLA), were employed to fabricate micro features. However, it is difficult to adjust and precisely manage, and it may be confined to specific materials. The running time and expense of MEMS-based processes, notably lithography-electroplating-molding (LIGA), deep reactive ion etching, and deep UV lithography, are often excessive. Just conductive materials can be machined using the WEDM process; optically reflecting materials cannot be machined using PLA; and because FIB removes materials at the atomic level, it is limited to delivering very low material removal rates [2-4]. As shown in Table 1.1 with their process applicability and constraints, the micro parts are manufactured using a variety of conventional and non-conventional micro manufacturing processes, including μ-drilling, μ-turning, μ-milling, μ-ultrasonic machining (μ-USM), μ-electric discharge machining (μ-EDM), pulse laser ablation (PLA), and μ-electric chemical machining (μ-ECM). Due to its affordability, superior relative accuracy, and potential to fabricate complex 3D structures, mechanical micromachining, particularly micromilling, is preferable over MEMS-based approaches. As noted in Fig. 1.1, this expansion is also evident in the nearly exponential rise in the number of peer-reviewed papers about these processes released since 2000.

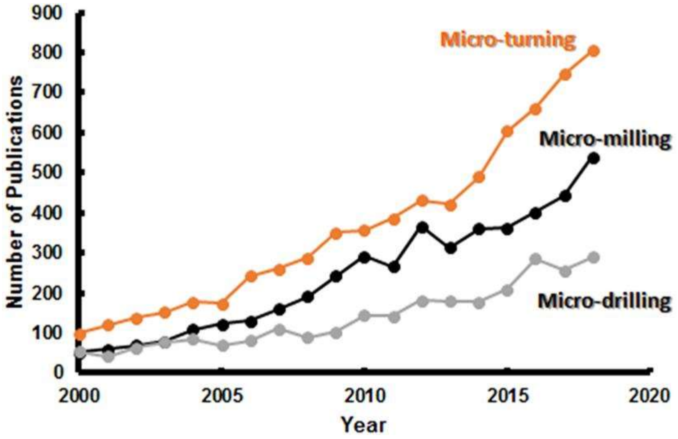

Fig. 1.1 Peer-reviewed papers about significant mechanical micromachining systems have increased over the last two decades [5].

Table 1.1 Aspects of different micro-manufacturing processes

Operation	**Manufacturing process and achievable surface roughness**	**Feasibility**	**Constraints**
μ-drilling [6]	Shearing through plastic deformation, R_a (min) < 0.1 μm	Regardless of conductivity, suitable in both soft and hard materials	Tool wear and failure
μ-turning [7]	Elastic plastic deformation, R_a (min) < 0.1 μm	Both soft and hard materials are suitable	Higher thrust force due to tool wear

μ-milling [8]	Shearing through plastic deformation, R_a (min) < 0.01 μm	Both soft and hard materials are suitable	Tool wear and failure
μ-EDM [9]	Melting and evaporation, R_a (min) = 0.3-0.7 μm	Hard as well as conductive material	Tool wear and heat affected zone
μ-USM [10]	Brittle fracture and cavitation by abrasive particles, R_a (min) = 0.3-0.7 μm	Hard and brittle materials	High tool wear and poor accuracy
PLA [11]	Fusion, vaporization, R_a (min) = 0.01 - 0.1 μm	Machining of metal and non-metal	Heat affected zone and accumulation of heat
μ-ECM [12]	Anodic dissolution by electrolysis, R_a (min) < 0.01μm	Electrically conductive materials	Higher processing time

Regarding the variety of materials, degree of accuracy, and intricacy of the part shape, it has substantial advantages compared to lithography-based micro-production procedures. Generally, the definition of micromachining is determined by the size of the cutting tool, which should fall between 1 μm and 1000 μm. Cutting edge radius and uncut chip thickness are also defined as having to be smaller than 5 μm and 10 μm, respectively, due to grain size and fabrication restrictions. Micromilling is often done using flat or ball end mills, which feature two flutes. Fig. 1.2 displays a graphic illustration of the milling operation. Cutting speed (calculated from rotational speed), feed rate (determined by feed per tooth or chip load), and depth of cut are controlling factors in micromilling operations. Cutting speed (V_c) and feed rate (v_f) are determined in Eqn. 1.1 and 1.2.

$$V_c = \frac{\Pi d n}{1000} \quad (1.1)$$

$$v_f = f_z \times n \times z_c \quad (1.2)$$

where n = rotational speed

f_z = feed per flute

d = diameter of tool

Z_c = number of flutes

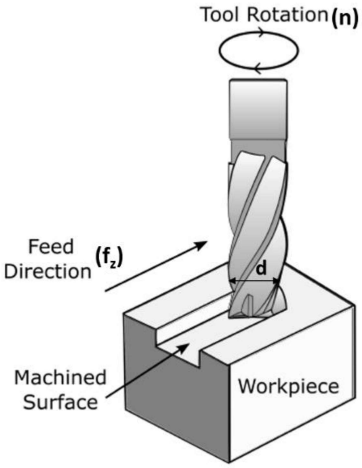

Fig. 1.2 Diagram of a milling tool cutting a workpiece [13]

There are numerous uses for micromilling in the aviation, healthcare, chemical, and electronics industries. However, often tool failure and quick tool wear, as well as the resulting alterations to the method of material removal, have an impact on the surface quality and dimensional accuracy of the component.

1.2 Sustainable machining techniques

Economic, social (operator's health and safety), and environmental variables are taken into account while assessing the sustainability evaluation indicators of the micro-milling technique [14]. Manufacturers are being forced to reduce the widespread utilization of cutting fluids due to strict global environmental regulations, concern for human health, and an understanding of environmentally friendly and sustainable manufacturing practises that adhere to the ISO 14000 guideline. Fig. 1.3 illustrates the different aspects of process sustainability and product sustainability in manufacturing sustainability. Therefore, the cost of the micro-cutting tool, the cost of the cutting fluid, the surface quality of the manufactured product, the consumption of the cutting fluid and energy, the volume of material removed, and the removal of the machining chips are all taken into account in the sustainability evaluation system of the micro-milling process.

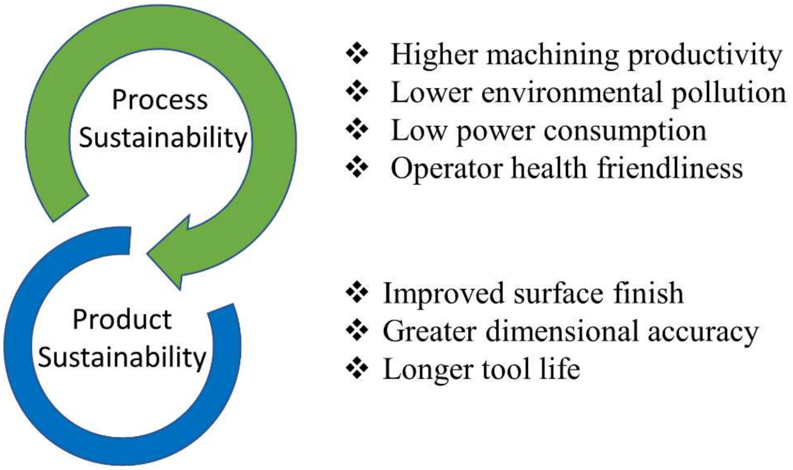

Fig. 1.3 Manufacturing sustainability [14]

Sustainable machining techniques are those that are utilized to enhance the overall effectiveness of the machining process. Dry machining with coated tools, cryogenic cooling, minimal quantity lubrication, minimal quantity lubrication with nanofluids, air and gas cooling, and solid lubricant are all categories of sustainable machining.

1.3 Motivation

The micro tool is susceptible to tool fracture because of its tiny size and inferior stiffness as a consequence of its enhanced slenderness ratio, that lowers productivity and the effectiveness of the micro milling process [8]. Additionally, the complexity of chip production caused by the size effect promotes relatively low surface quality and faster tool wear. The evolution of wear-resistant coatings and cooling with lubrication are two approaches to tackling this problem [15].

According to earlier research, more than 85% of coolants used globally in manufacturing industries are based on petroleum-based products. However, hydrocarbon oils and related compounds have a significant negative influence on the environment and human health. Hence, various environmentally friendly cutting and lubricating solutions have been reported to address these problems [16, 17]. In order to address the thermal and friction issues during machining, a variety of cooling techniques are used in conventional machining, including flood cooling, high-pressure cooling, cryogenic cooling, atomization-based cutting fluid mist systems, minimum quantity lubrication (MQL), bio-lubricant-based MQL, and nanofluids-based MQL (NF-MQL) [18-22]. In the MQL method, the air atomizing nozzle produces micrometer-sized liquid droplets using compressed air, which are then delivered straight into the machining area. Sustainability is promoted, and cutting fluid usage is decreased. Additionally, the solid nanoparticles in the NF-MQL system have improved the performance of the MQL system due to the intrinsic characteristics of nanofluids, such as their capacity to carry heat, tribological characteristics, antifriction qualities, and wettability features.

Applying thin film coating to microtools can extend tool life by reducing friction between the milling cutter and the workpiece. As a result, it is thought that pairing the use of coated tools with NF-MQL can further improve micro-machinability. However, no studies in this area have yet been found. There have been very few studies done on Ti-6Al-4V alloy micromilling, despite the fact that thin-film coated tools and NF-MQL have been extensively published for the conventional machining of this alloy. Additionally, to the best of our knowledge, no published literature has described the hybridization of nanofluids-based MQL with thin-film coated tools in the micromilling of Ti-6Al-4V alloy.

1.4 Research objectives

This research aims to study the use of coated tools and nanofluids based MQL as alternatives to conventional cutting fluids in micro-machining and to find ways to improve the machinability of Ti-6Al-4V in micromilling. Overall, four primary factors are being continued to improve: coated tools, cutting fluids, cutting fluid application methods, and nanoparticles in cutting fluids. The objectives of the research are outlined as follows:

a) To look through the literature on manufacturing difficult-to-machine alloys to determine the current state-of-the art constraints and potential for progress;
b) To investigate how thin-coated tools and nanofluids in MQL together could help improve the machinability of difficult-to-cut titanium alloys;
c) To determine how cooling and lubrication affect the size effect in micro milling;
d) To examine the usage of nanoparticles like spherical CuO and nanoplatelet MoS_2 in micro-milling to improve performance and provide lubrication;
e) To study the micro-machining of titanium alloy at both the plowing and shearing zones and understand the influence of the size effect on machining responses and
f) Utilizing various cooling and lubrication conditions, analyze the cutting forces, tool wear, burr formation, and surface roughness.

1.5 Thesis outlines

This thesis is divided into seven chapters as follows:

Chapter 1 Introduction explains the research's motive, purpose, and goals.

Chapter 2 discusses the two main topics of the research, (1) environmentally friendly cutting fluids and (2) coated tools to enhance machining performance, in detail, and gives a thorough overview of the literature in these areas. It also discusses difficulties with micromilling, and research gaps, and the need for more exploration.

Chapter 3 describes the experimental details employed in this research work, including workpiece material characterization, machine tools, experimental set-up, and analytical equipment.

Chapter 4 reports on experimental work performed to compare different coated tools with various cutting environments with MQL concurrently in micromilling of Ti-6Al-4V alloy. The outcomes of tool wear, cutting forces, surface roughness, burr formation, texture, wettability, and stability of water-based CuO nanofluids are assessed.

Chapter 5 reports experimental work comparing different cutting environments (dry, soybean oil MQL, soybean oil-based CuO, MoS_2, and hybrid CuO-MoS_2 nanofluids MQL) with AlTiN coated WC micro-mill in micromilling of Ti-6Al-4V alloy. The outcomes of tool wear, cutting forces, surface roughness, burr formation, surface texture, wettability, and tribological behavior of soybean oil-based nanofluids are reviewed.

Chapter 6 reports on the experimental work undertaken in microscale milling to study the effects of paraffin oil and vegetable oil (soybean oil) emulsions with different MQL flow rates on cutting forces, burr width, surface roughness, and topography.

Chapter 7 presents conclusions and a summary of the research work. Suggestions and recommendations for future work initiatives are also provided.