

Research on cutting performance of micro-texturing tools for cutting aluminum alloys

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Abstract. To address the common issues of high cutting forces, poor surface quality, and chip wrapping in aluminium alloy machining, this study innovatively designed two types of micro-groove textures on the tool surface based on the natural flow direction of chips: one parallel to and the other perpendicular to the main cutting edge (micro-texture width: 50 μm , micro-texture depth: 50 μm , micro-texture edge distance (distance from the main cutting edge): 200 μm , micro-texture spacing: 200 μm). At a cutting speed of 1250 r/min, a feed rate of 0.15 mm/r, and a cutting depth of 0.1 mm, Through finite element simulation analysis of cutting force, temperature, stress, and chip morphology, and using laser processing technology to precisely prepare micro-textured tools for actual cutting experiments, the study systematically evaluated the impact of microtextures on performance. Furthermore, this study integrated composite solid lubricants into the microgrooves to develop self-lubricating tools and investigated the synergistic effects of cutting speed and lubrication conditions on the performance of micro-textured tools. The results showed that micro-textured tools significantly reduced cutting force, stress, and temperature, improving friction and heat dissipation. Among them, self-lubricating micro-textured tools performed particularly well, further reducing cutting force (with a maximum reduction of 20.39%), improving surface quality (roughness of 1.421 μm), and optimizing chip morphology. The novelty of this study lies in the synergistic optimization of heat dissipation, friction reduction, and chip removal performance through micro-texture orientation design and solid lubricant-assisted machining. This technology provides an effective solution for enhancing the efficiency and quality of aluminium alloy machining.

Keywords: Turning / aluminum alloys / micro-texturing / solid lubricants / surface roughness

1 Introduction

Consequently, aluminum alloys exhibit broad applicability across sectors such as aviation, aerospace, advanced health-care, and automotive, as demonstrated by research [1–3]. However, their relatively low melting point renders them susceptible to thermal softening of chips during machining, resulting in adhesion to the cutting blade. This adhesion subsequently leads to localized heating of the tool, significantly compromising its durability and adversely affecting machining precision, as reported in references [4–5].

Wang, B et al. [6] significantly improved the efficiency of machining aluminum alloy materials by adjusting the cutting parameters and the tool's working angle. They discovered that a tool with a positive front angle is crucial for the machining process. During final cuts, precision is essential, and reducing the thickness of the cuts is important. In another study, Umroh, B et al. [7]

investigated the optimal conditions for rapid processing of aluminum alloy using uncoated cemented carbide tools. They developed a mathematical model using multivariate linear regression based on the collected data. Through experimental trials and the identification of ideal cutting conditions using multi-objective genetic algorithms, they achieved a surface roughness as low as 1.22 μm with a cutting speed of 1000 m/min and a feed speed of 0.12 mm/rev. Zhang, P et al. [8] examined how cutting factors affect the microstructure development and damage process in the micro-cutting of 7075-T6 aluminum alloy. They found that the onset and spread of surface cracks varied significantly under different cutting conditions. At shallower cutting depths, the wear of micro-cutting tools was primarily due to oxidative wear.

Recently, advancements in bionics and tribology have revealed that smoother surfaces do not necessarily equate to greater wear resistance. The introduction of the friction reduction theory for non-smooth surfaces has sparked a renewed investigation into methods for reducing friction and preventing the deterioration of tool surfaces [9–11].

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To enhance the cutting efficiency of tools and improve the quality of machined parts and components, relevant researchers and academics have refined the cutting capabilities of tools by creating micro-textures on their surfaces, thereby altering the friction conditions on the tool's front surface [12,13]. Zhang, N. et al. [14] conducted slicing experiments at various velocities and depths using micro-textured instruments. They discovered that these tools significantly reduced wear on both the front and rear surfaces of the tool, improved surface durability, minimized oxidation occurrences, and elevated the machining quality of titanium alloy workpieces. Wang, Q. et al. [15] employed lasers to create micro-textures on diamond tool surfaces and analyzed the friction properties and cutting efficiency of these tools. They found that the cutting force and friction coefficient decreased notably when using micro-textured diamond tools, while the cutting efficiency of single-crystal diamond tools saw a marked enhancement. Patel, K. et al. [16] examined how micro-texture factors influence the cutting efficiency of dry turning titanium alloys. They revealed that the width, depth, and proximity of the micro-texture to the cutting edge had a significant impact on the cutting forces. Additionally, they found that the feed rate significantly influenced both the cutting forces and tool wear. The aforementioned studies demonstrate that micro-textures on the tool's front surface enhance its cutting efficiency. However, in dry conditions, the tool remains in immediate and direct contact with the workpiece, experiencing severe and prolonged resistance on its surface due to intense heat and pressure, often leading to surface wear.

Pertinent scholars in the field have developed a self-lubricating device by infusing solid lubricants into the micro-textured areas of the tool. This innovation aims to supply lubrication to the tool's cutting zone through the self-lubricating properties of its surface, thereby reducing the complex friction on the tool's surface under dry cutting conditions and enhancing its cutting efficiency [17–19]. Musavi, S. and his colleagues [20] utilized laser technology to create micro-textures on the tool's surface and conducted cutting experiments in both dry and micro-lubricated states. Their findings revealed that both the micro-textured tool and the micro-lubricated tool exhibited reduced surface wear. Sahinoglu, A. and his team [21] performed slicing experiments using various parameters across three conditions: dry, coolant, and micro-lubrication. Their results showed minimal surface texture, vibration, and energy usage in the micro-lubrication condition. Additionally, the cutting efficiency peaked in the micro-lubrication scenario, achieving optimal cutting parameters of 145 m/min velocity, 0.1 mm/rev feeding speed, and 0.3 mm cut depth.

As the manufacturing industry continues to develop, increasingly stringent requirements are being placed on the cutting performance and wear resistance of cutting tools. During the machining of aluminum alloys, their high chemical reactivity can lead to elevated cutting temperatures, triggering chemical reactions between the tool and workpiece, resulting in the formation of compounds that create built-up edges and compromise surface quality; Additionally, the high specific heat capacity of aluminum

alloys causes approximately 75% of the cutting heat to accumulate at the tool-workpiece interface (rather than being carried away by the chips), which not only exacerbates chemical reactions but also enhances the adhesion of softened aluminum alloys to the tool. However, current research has primarily focused on materials such as steel, with insufficient attention given to the unique heat accumulation and adhesion issues specific to aluminum alloys. Therefore, this study aims to effectively improve the heat accumulation phenomenon in aluminum alloy cutting by designing microtextures on the tool surface while ensuring basic cutting performance. To achieve this goal, microtextured tools with two types of grooves—parallel to the main cutting edge and perpendicular to the main cutting edge—were first prepared based on the actual chip flow direction of aluminum alloys; Subsequently, finite element simulation analysis was conducted to investigate the cutting forces, temperatures, stresses, and chip morphology during machining with these tools, systematically studying the influence of the spatial relationship between the microtexture and the main cutting edge on machining performance. Additionally, actual machining experiments were conducted to validate the simulation results. Furthermore, self-lubricating tools were fabricated by incorporating solid lubricants into the microtexture to explore the effects of tool surface lubrication conditions and changes in cutting speed on machining performance.

2 Mater cutting tests

2.1 Test materials and experimental equipment

To examine how the speed of cutting impacts the surface texture and the cutting power in 7075 aluminum alloy machining, the process of dry cutting an aluminum alloy bar utilized a CA6140A lathe, adjusting the speeds to 1250 r/min, 1000 r/min and Three sets of cutting tests were conducted, each with a speed of 800 revolutions per minute, a back draft ap of 0.1 mm, and a feed speed of 0.15 mm/r, resulting in the collection of three sets of cutting specimens. The tool employed in the experiment is a PCBN cutting tool, with the workpiece being a cylindrical aluminum alloy bar with a diameter of 50 mm and a length of 150 mm. Prior to the cutting experiment, the aluminum alloy bar underwent surface pretreatment involving rough turning to remove surface burs and scratches. A center hole was also drilled at the top end of the bar, which served as the positioning datum during the subsequent machining process, ensuring the accurate positioning of the workpiece on the lathe and fulfilling the roles of positioning and support.

During the aluminum alloy cutting experiment, to collect the cutting forces generated during the process, a Kistler 9527B force measuring instrument was installed at the bottom of the tool post for three-directional cutting force measurement. The force measuring instrument comprises four three-directional force sensors installed between a base plate and a top plate. Each sensor contains three pairs of quartz plates, with one pair sensitive to pressure in the z -direction and the other two pairs sensitive to shear forces in the x and y directions, respectively.

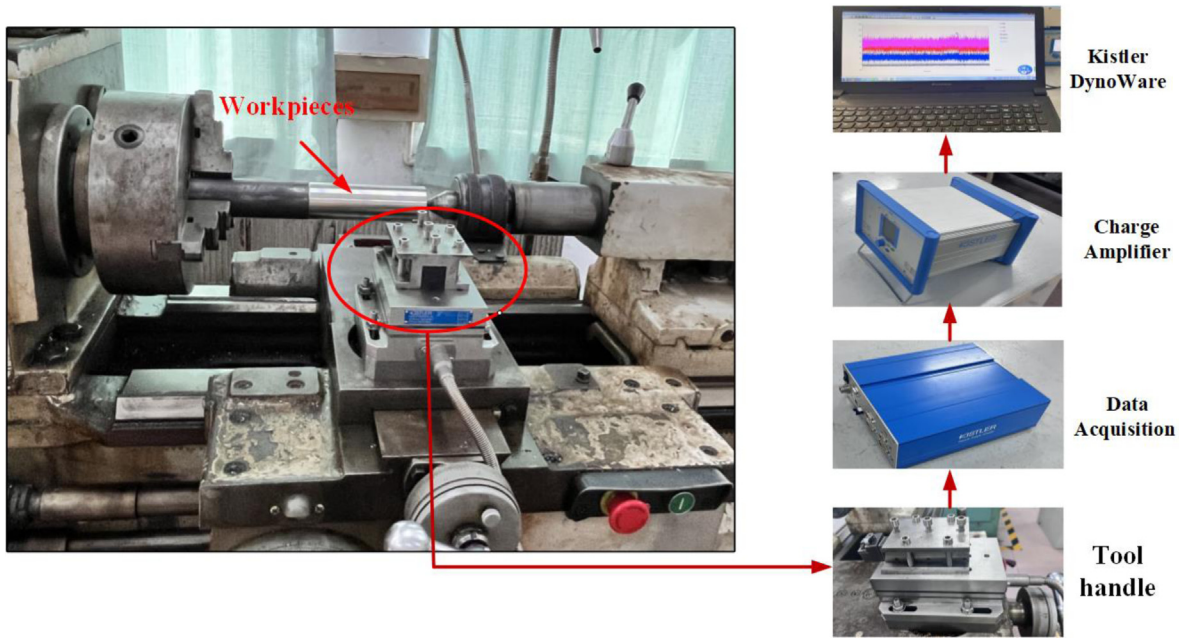


Fig. 1. The test equipment.

When an external force acts on the force measuring instrument, it causes deformation of the quartz plates. Due to the piezoelectric effect, this deformation leads to the generation of charges on the quartz plates. The generated charges are amplified by a charge amplifier and then converted into digital signals through an A/D data conversion board. These digital signals are received and processed by a computer to obtain the values of the external forces. The experimental setup is illustrated in Figure 1. After the cutting process, the surface roughness of the workpiece was measured multiple times using a ZeGageTM Pro three-dimensional profilometer to investigate the impact of different cutting speeds on surface roughness and cutting forces.

2.2 Analysis of test results

As depicted in Figure 2a, the force exerted during the cutting of an aluminum alloy is gathered and charted, illustrating the effect of cutting speed on the cutting process, revealing that under identical operational conditions, the cutting speed increases, the cutting force keeps increasing, in contrast to the cutting speeds of 800 r/min, 1000 r/min, and 1250 r/min, enhancing the cutting force by 12.65% and 24.34% respectively. The increase in cutting speed, enhanced rate of material removal per time unit, severe deformation of the workpiece's cutting layer material, and heightened wear on the tool's surface all contribute to this, culminating in an augmented cutting force.

As depicted in Figure 2b, the roughness of the machined aluminum alloy bar's surface was gathered and graphically represented, illustrating how the speed of cutting influences this roughness, with Sa representing the arithmetic mean height of the face and Sq the root mean square height and The peak height is denoted as Sz. The graph reveals an

increase in Sa, Sq, and Sz correlating with higher cutting speeds, and a surface roughness Sa of $1.751\mu\text{m}$ at 800 r/min. In contrast to 800 r/min, there's a 3.43% and 11.19% rise in surface texture at 1000 r/min and 1250 r/min, respectively. The increase in cutting speed results in heightened friction on the tool's surface, amplified cutting force, and a faster rate of material removal, making the machined chips readily accumulate on the surface of the tool experiences an increase in its local temperature, and the ease of adhering the chips to it leads to abrasion, thereby reducing the precision of machining.

During the cutting test of aluminum alloy materials, a phenomenon was clearly observed where chips wrapped around the already machined surface of the aluminum alloy material, as shown in Figure 3. From the figure, it can be seen that as the workpiece rotates rapidly and the machining process progresses, more and more chips wrap around the surface of the workpiece, making it difficult for them to break off. This is due to the varying surface hardness of the aluminum alloy material, caused by differences in alloy composition or heat treatment, resulting in uneven hardness across the surface and increasing the complexity of the machining process. Additionally, due to aluminum alloy's low density and excellent ductility, especially during high-speed cutting, it is prone to forming long and flexible filamentary chips, which easily wrap around the surface of the workpiece. The heat generated during cutting affects the plasticity of the aluminum alloy, making the chips softer and more prone to bending and wrapping around the tool.

From the above aluminum alloy cutting experiments conducted at different speeds, it can be inferred that traditional cutting conditions often lead to issues such as increased cutting forces, poor machining quality, and chip winding around the machined surface. The main reasons for chip winding are the inherent properties of aluminum

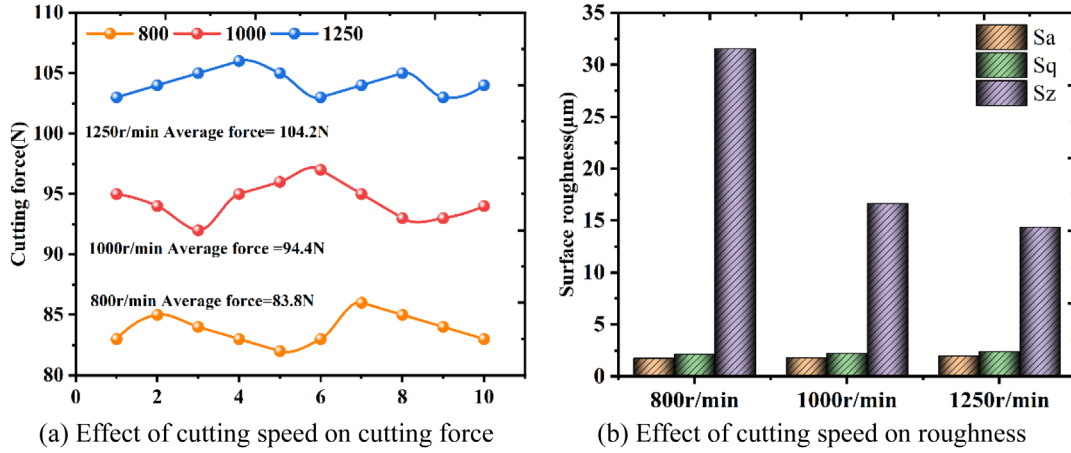


Fig. 2. Cutting force and surface roughness.

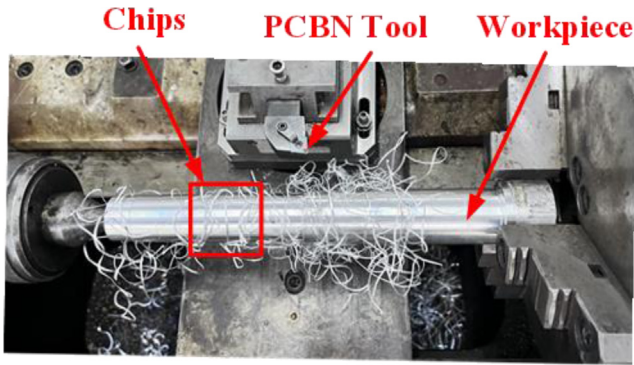


Fig. 3. Cutting entanglement phenomenon.

alloy and the choice of parameters and tool design during the cutting process. Therefore, by modifying the surface structure of the tool, altering the friction state between the tool and the chips during cutting, and optimizing the cutting performance of the tool, the machining quality of aluminum alloy can be improved.

3 Finite element simulation experiment of aluminum alloy cutting by micro-textured tools

3.1 Micro-textured tool modeling

To optimize the cutting performance of tools when machining aluminum alloys, micro-textures are fabricated in the working area of the tool's rake face, leveraging their friction-reducing and wear-resistant properties to enhance the tool's operational performance. To investigate the impact of these micro-textures on cutting performance, this paper designs two types of micro-textures based on the chip flow direction: vertical grooves perpendicular to the main cutting edge and parallel grooves parallel to the main cutting edge, as shown in Figure 4. Figure 4 illustrates the distribution of groove-type micro-textures on the tool edge, with both types of micro-textures having identical shape

and size parameters. Specifically, the width of the micro-textures is 50 μm, the depth is 50 μm, the edge-to-texture distance (from the main cutting edge) is 200 μm, and the spacing between micro-textures is 200 μm.

3.2 Finite element simulation test of micro-textured tools

The crafted 3D representation of the instrument is integrated into the simulation program for slicing simulations. The material for the workpiece consists of 7075 aluminum alloy, while the PCBN tool serves as the tool material, and the test's cutting dosage is specified as the cutting speed a flow rate of 1250 r/min, a flow rate of 0.15 mm/r, and a cutting depth of 0.1 mm. Throughout the slicing procedure, the starting environmental temperature is maintained at 20 °C. In the course of the simulation, a constant limitation was applied to the tool, and the workpiece underwent rotational movement. To enhance the precision of the simulation and reduce the duration of the simulation, the tool's largest mesh size should be positioned away from the cutting layer. The region has been adjusted to 0.1 mm, with the micro-texture part's refinement dimension fixed at 0.01 mm; the workpiece's largest size distant from the cutting layer is fixed at 3 mm, and the surface's cutting layer mesh undergoes refinement. Figure 5 displays the meshing of the tool and workpiece using finite element simulation. The cutting simulation enables the extraction of data related to the chip formation process, generation of heat in the cutting zone, and the friction characteristics of tools and chips. Created during the simulation phase for analytical purposes, offering a theoretical foundation for the real-world cutting examination.

3.3 Cutting simulation results and analysis

3.3.1 Effect of micro-texture on cutting forces

The force exerted during the metal cutting process by the tool is known as the cutting force. This factor plays a crucial role in the cutting procedure, closely linked to the quality of machining, the lifespan of the tool, and the load on the machine tool. Following the completion of the

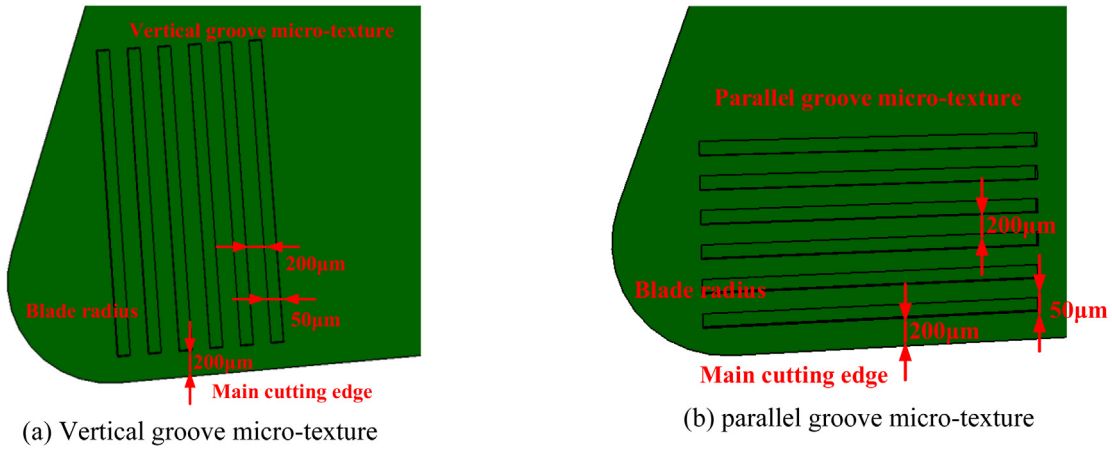


Fig. 4. Micro-texture tool morphology.

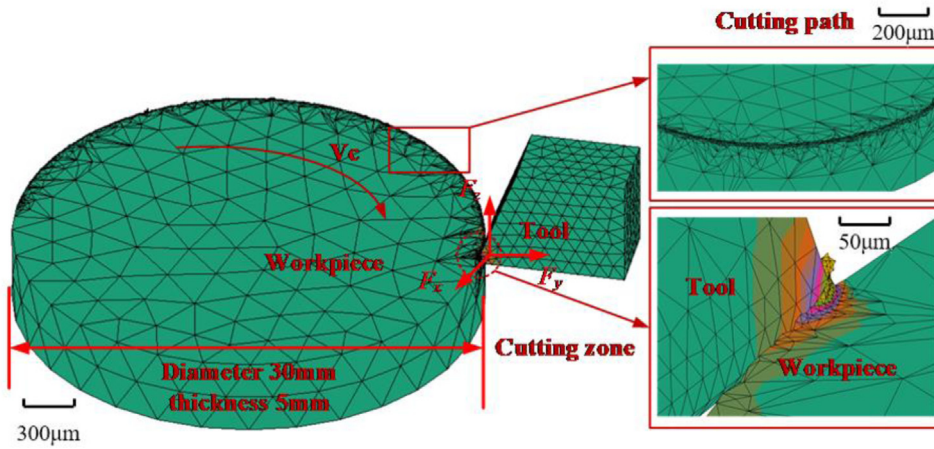


Fig. 5. Tool and workpiece meshing.

aluminum alloy cutting simulation test, the simulated cutting force data is gathered and analyzed, with the micro-textural impact on the cutting force depicted in Figure 6a. The diagram illustrates that when the cutting quantity is identical to that of conventional tools, both parallel and perpendicular groove micro-textured tools enhance the reduction of cutting force, with parallel groove micro-textured tools promoting stress reductions of 23.84% and 19.28%, respectively. This is due to the presence of surface micro-textures, which reduce the cutting force and consequently the force acting on the tool surface, leading to a decrease in stress.

The primary effect of micro-textured tools in the 1 groove is the reduction of cutting force. Microtextured tools for parallel and vertical flutes resulted in a decrease in cutting force by 20.69% and 11.72%, respectively, in comparison to traditional tools. The creation of a micro-texture within the cutting area of the tool's surface accounts for this. This enhances the tool surface's friction condition owing to its micro-texture and lowers the friction coefficient, thereby decreasing the cutting force. In metal cutting processes, the tool tip is the first to enter the workpiece cutting layer, making it the area that bears the maximum load and shear force. When stress concentrates in this area, it leads to increased friction and wear at the contact point between the tool tip and the workpiece. Therefore, it is necessary to collect the stress generated on the tool surface during the cutting simulation process and extract the surface stress values for traditional tools, parallel-groove micro-textured tools, and

vertical-groove micro-textured tools. Three points are collected from the surface of each tool to create a diagram showing the influence of micro-textures on stress, as illustrated in Figure 6b. The diagram reveals that compared to traditional tools, micro-textured tools contribute to a reduction in stress values, with parallel-groove micro-textured tools and vertical-groove micro-textured tools promoting stress reductions of 23.84% and 19.28%, respectively. This is due to the presence of surface micro-textures, which reduce the cutting force and consequently the force acting on the tool surface, leading to a decrease in stress.

Figure 7 displays the normal stress distribution on the surfaces of the three types of tools. The stress distribution diagrams for all three tools use the same legend, ensuring consistency. From the diagrams, it can be seen that for traditional tools, compressive stress appears at the cutting edge of the tool tip, with tensile stress manifesting internally. Stress gradually spreads from the tool tip, showing a decreasing trend in all surrounding areas. For micro-textured tools, compressive stress also appears at the tool tip, but the micro-texture area on the rake face of the tool is more prone to compressive stress concentration. This is because the edges of the micro-textures are

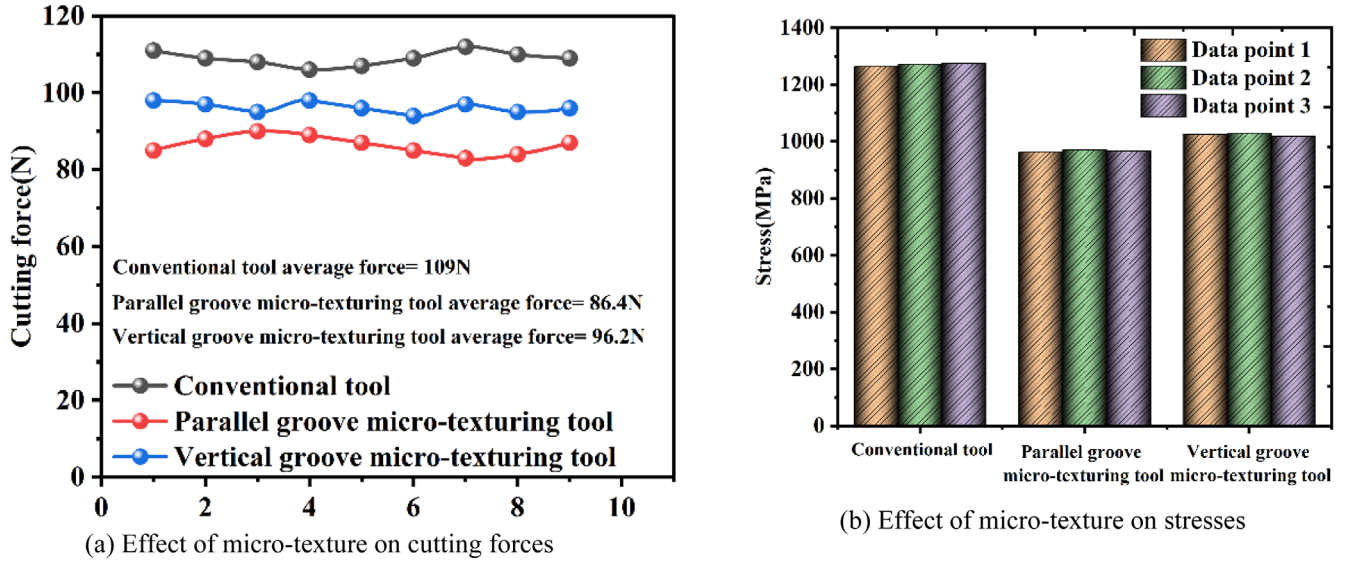


Fig. 6. Cutting forces and stresses.

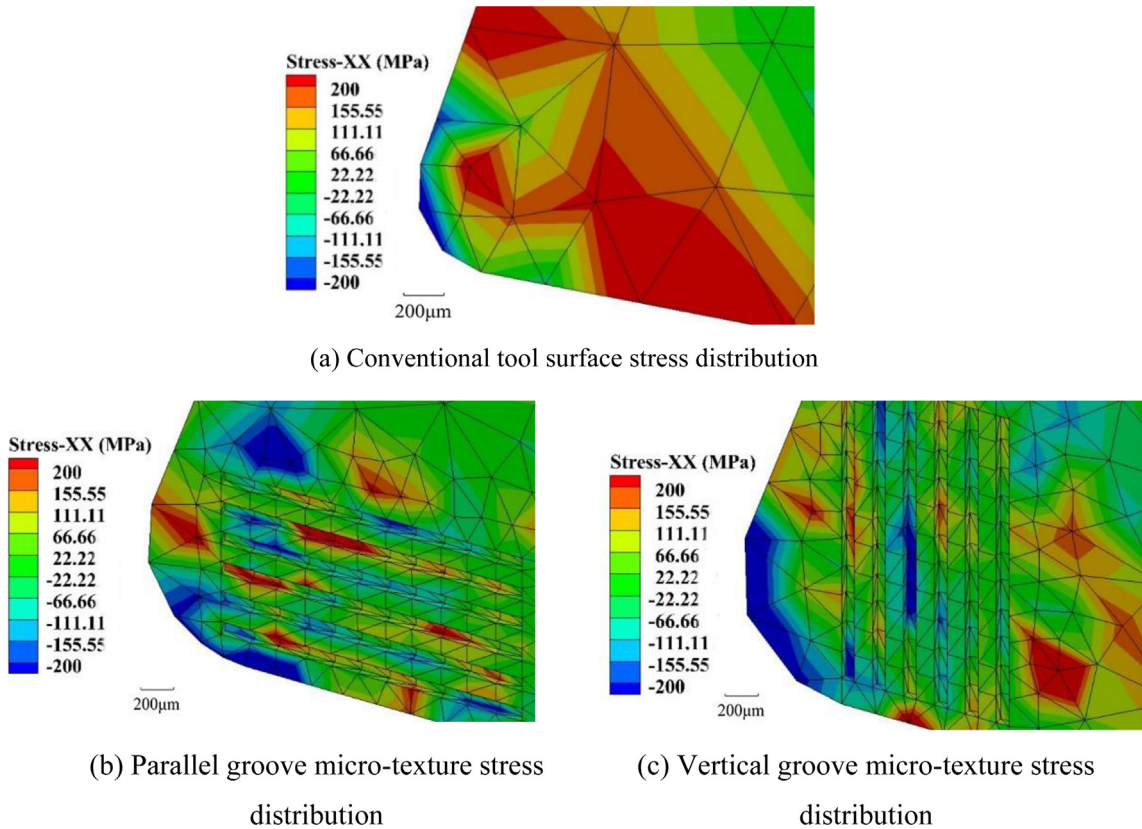


Fig. 7. Stress distribution on tool surface.

perpendicular to the tool surface, and during cutting, the sharp corners of the micro-texture edges are more likely to cause stress concentration. During the cutting process, the tool surface is subjected to the combined effects of high temperatures and cyclic stresses, which may lead to the generation of thermal stress cracks. Especially in the cutting area of the rake face of the tool, where the temperature rises above the internal material temperature,

the surface expands more than the internal material due to thermal expansion. This expansion is constrained by surrounding materials, resulting in compressive stress. In non-working areas of the rake face, due to heat transfer and convection between the tool and the air, the temperature of the surface material of the rake face decreases faster than the internal material, leading to the formation of tensile stress. This cyclic thermal stress may cause cracks to form

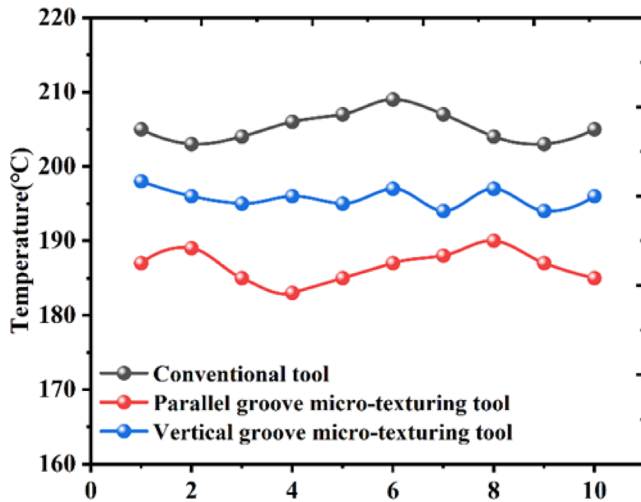


Fig. 8. Effect of micro-texture on cutting temperature.

on the tool surface, thereby affecting the durability and cutting efficiency of the tool. For micro-textured tools, the micro-textures alter the location of stress concentration on the tool surface, causing micro-cracks to initiate and propagate at the edges of the micro-textures, thus enhancing the durability of the tool.

3.3.2 Effect of micro-texture on cutting temperature

During metal cutting, when the tool contacts the workpiece and performs cutting, the tool cuts into the workpiece surface and removes material. At this point, the tool must overcome the hardness and toughness of the material, thereby consuming energy. A portion of this energy is converted into heat. Additionally, during the cutting process, friction between the tool surface and the workpiece also generates heat. This heat originates from the relative motion between the tool and the workpiece, particularly during high-speed cutting or deep cutting, where friction heat increases significantly. Consequently, to illustrate the impact of the micro-texturing tool on the cutting temperature, data on the tool's surface heat during the simulation is gathered, as depicted in Figure 8. The illustration reveals that micro-texture on the tool's surface aids in lowering cutting temperatures, where, in contrast to traditional tools, parallel and vertical flute micro-texture tools excel. Advocate for lowering the cutting temperature by 9.11% and 4.63%, in that order. The micro-texture on the tool's surface enlarges its heat dissipation zone, and under identical cutting dosage scenarios, the micro-texture tool circumvents direct contact with the cutti. The region of both the tool and the workpiece's cutting layer reduces the intricate friction on the tool's surface, thereby lowering the cutting temperature there.

Figure 9 presents the surface temperature contour maps of three types of cutting tools at the same simulation time step. From the maps, it is evident that the legends for the temperature contours of the three tools are identical. The high-temperature regions tend to concentrate at the tool tips and gradually spread towards the interior of the tools. The boundary between the

high-temperature and low-temperature regions is very distinct, and as the working duration of the tools increases, significant heat accumulation occurs at the tool tips. Observing Figures 9b and 9c, it can be seen that the high-temperature regions at the tool tips of the micro-textured tools with parallel and vertical grooves are smaller, indicating enhanced heat dissipation performance on the tool surfaces. This is due to the presence of micro-textures on the tool surfaces, which results in non-intimate contact between the tool and the workpiece, thereby increasing the heat dissipation space on the tool surface and reducing the surface temperature. Since aluminum alloy materials are prone to softening when heated, the presence of micro-textures prevents the softened aluminum alloy chips from adhering to the tool.

3.3.3 Influence of micro-texturing on chips

Typically, aluminum alloys are pliable and are prone to creating elongated, slender chips when machined. The chips encircle both the tool and the machined workpiece's surface, causing swift deterioration of the tool's edges, thereby shortening its lifespan. Should the chips be Should the chips remain undischarged over time, they will either embed or graze the workpiece's surface, leading to increased surface roughness, thereby impacting the precision and quality of the components. Consequently, this document compiles the chips produced in the cutting simulation phase, with Figure 10 illustrating the topography of the chips produced by three distinct tools.

From the figures, a comparative analysis of the three types of cutting tools reveals that when using a traditional cutting tool to machine aluminum alloy, long chips are formed, which curl towards the tool surface. The temperature of the chips increases significantly at the bending points. In contrast, the chips produced by the parallel groove micro-textured tool have a lower surface temperature and result in more fine chips. Most of these fine chips escape along the direction of the micro-textures, carrying away a significant portion of the heat generated during cutting. For the vertical groove micro-structured tool, only a small amount of fine chips flow along the tool surface, while most of the chips bend towards the tool surface, resulting in higher chip temperatures. Thus, it can be concluded that the parallel grooves micro-textured along the main cutting edge facilitate the bending and breaking of chips. Additionally, these parallel grooves can capture and store tiny chips that remain on the tool surface within the micro-textures, preventing them from entering the cutting zone and causing abrasive wear. Since the shape of the micro-textures is similar to the flow direction of the chips, the parallel grooves micro-texture promotes the outflow of chips, avoiding chip accumulation on the tool surface and subsequent localized temperature rise.

To sum up, simulating the cutting of three varieties of tools on aluminum alloy materials reveals that creating micro-textured material in the tool surface's cutting area aids in diminishing cutting force, stress, and cutting te In terms of temperature, the micro-textured tool with a parallel groove, aligned with the primary cutting edge, outperforms the other two tool types considerably.

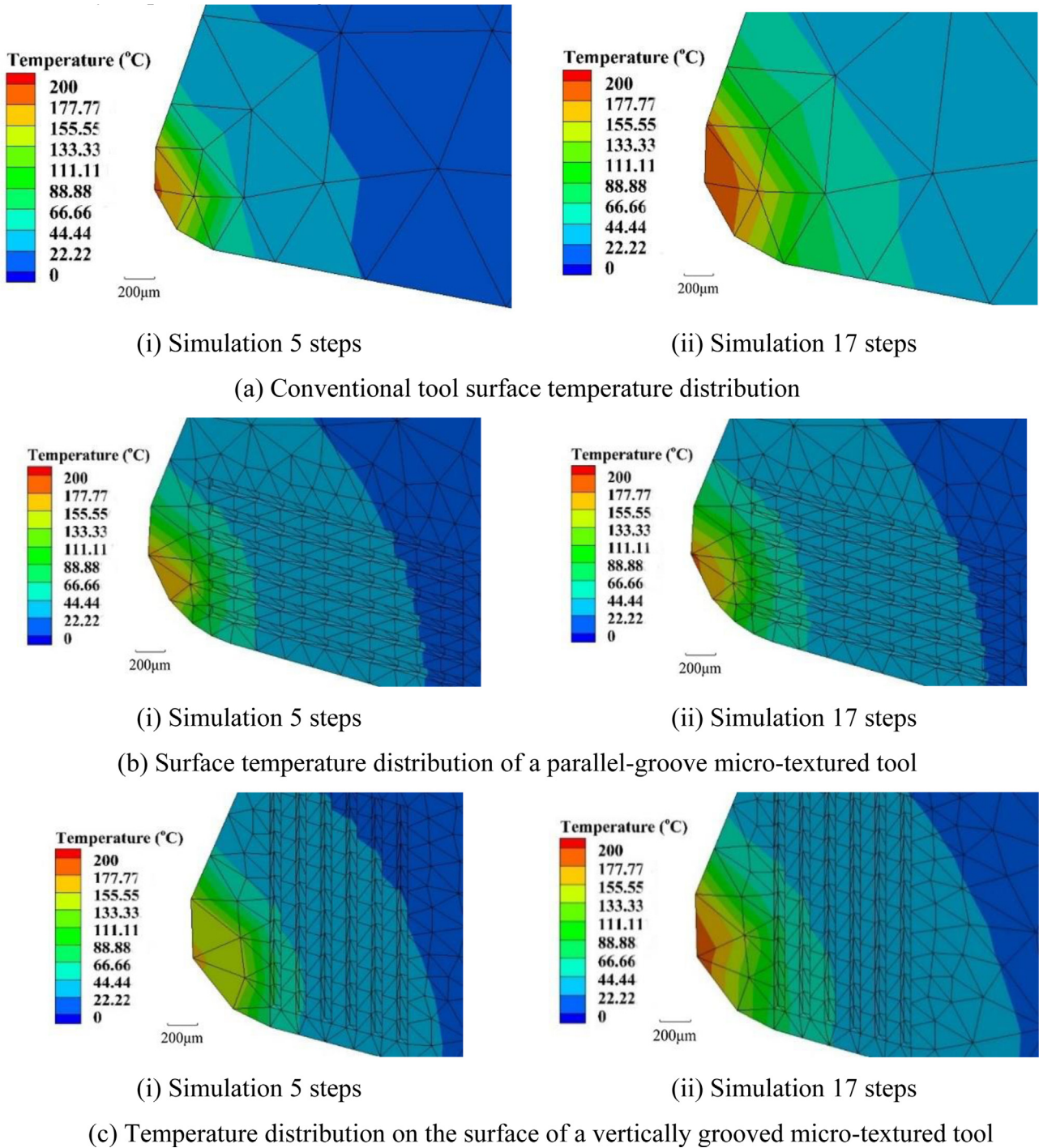


Fig. 9. Tool surface temperature distribution cloud.

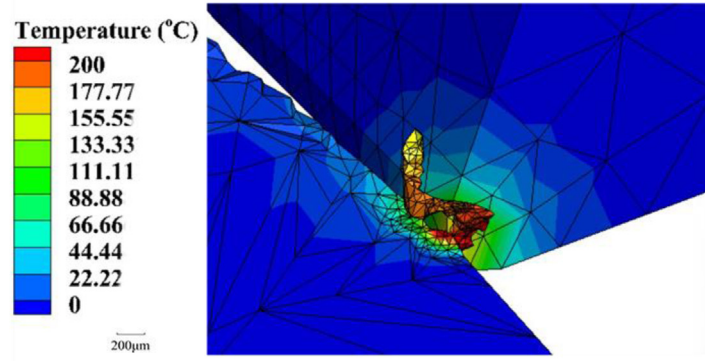
4 Cutting test of aluminum alloy by micro-textured tools

To confirm the simulated outcomes of slicing aluminum alloys, real cutting tests were conducted to explore how micro-texture influences cutting and surface texture. Concurrently, the construction of a self-lubricating device was completed. through the application of solid lubricant

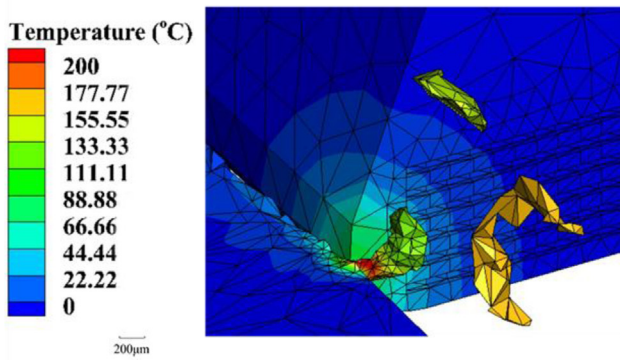
in the micro-texture zone, and the impact of this micro-texture on cutting efficiency was compared between dry and self-lubricated states.

4.1 Micro-textured tool preparation and test program

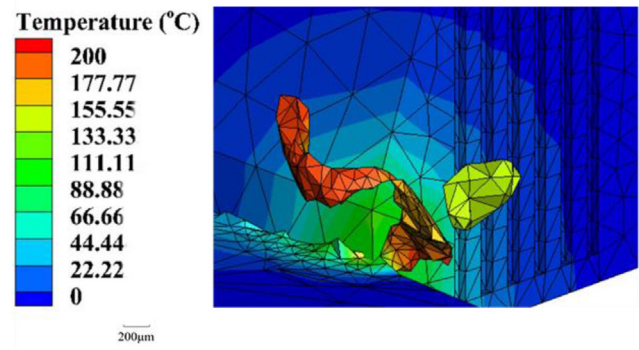
The development of micro-texture within the tool surface's working zone has become a focal point for research aimed at enhancing the tool's cutting efficiency lately, primarily by



(a) Conventional tool chip morphology



(b) Chip morphology of a parallel fluted micro-textured tool



(c) Chip morphology of vertically fluted micro-textured tools

Fig. 10. Chip shape of the tool.

machining the surface to create micro-texture at the nano or micron scale, and enhance the tool's efficiency through the application of the micro-texture's action mechanism on its surface. Currently, prevalent techniques for micro-texturing include laser processing, photolithography, and micro-electrical discharge technology, etc. Nonetheless, the utilization of laser processing in creating micro-texturing tools is prevalent due to its benefits in high precision, precise control, and broad applicability [22–26]. This document discusses both the micro-textured and perpendicular grooves in parallel. For real-world cutting tests, micro-textured tools are crafted with lasers, as depicted in Figure 11. Once the laser machining processing settings are established, a simulated pad is placed on the table to stop laser machining from reaching the carrier table, followed by the creation of a tool positioning line on the pad for tool placement. Modify the focal length for focus, position the instrument on the carrier table and insert the desired shape into the laser for processing, as depicted in Figure 11.

During dry cutting machining, the absence of oil lubrication on the tool's surface leads to intense friction, elevating the cutting temperature and causing increased wear on the tool surface. Consequently, this document argues Enhances the cutting efficiency of a self-lubricating instrument by incorporating a solid lubricant blended with molybdenum disulfide and antimony trioxide into its

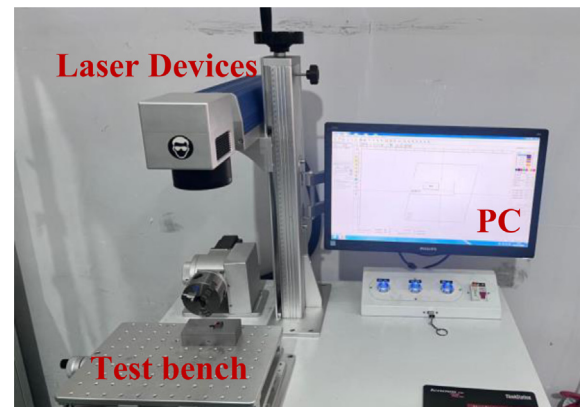


Fig. 11. Laser processing equipment.

micro-textured section. Within this group, molybdenum disulfide (MoS_2) stands out as a frequently utilized solid lubricant due to its superior resistance to wear, its ability to create a durable lubricant layer in conditions of high temperature, pressure, and heavy load, its capacity to diminish friction and wear, and its ability to extend the service lifespan of mechanical components [27,28]. Nonetheless, due to the prolonged exposure of the tool's surface to elevated temperatures and pressures, the rise in temperature within

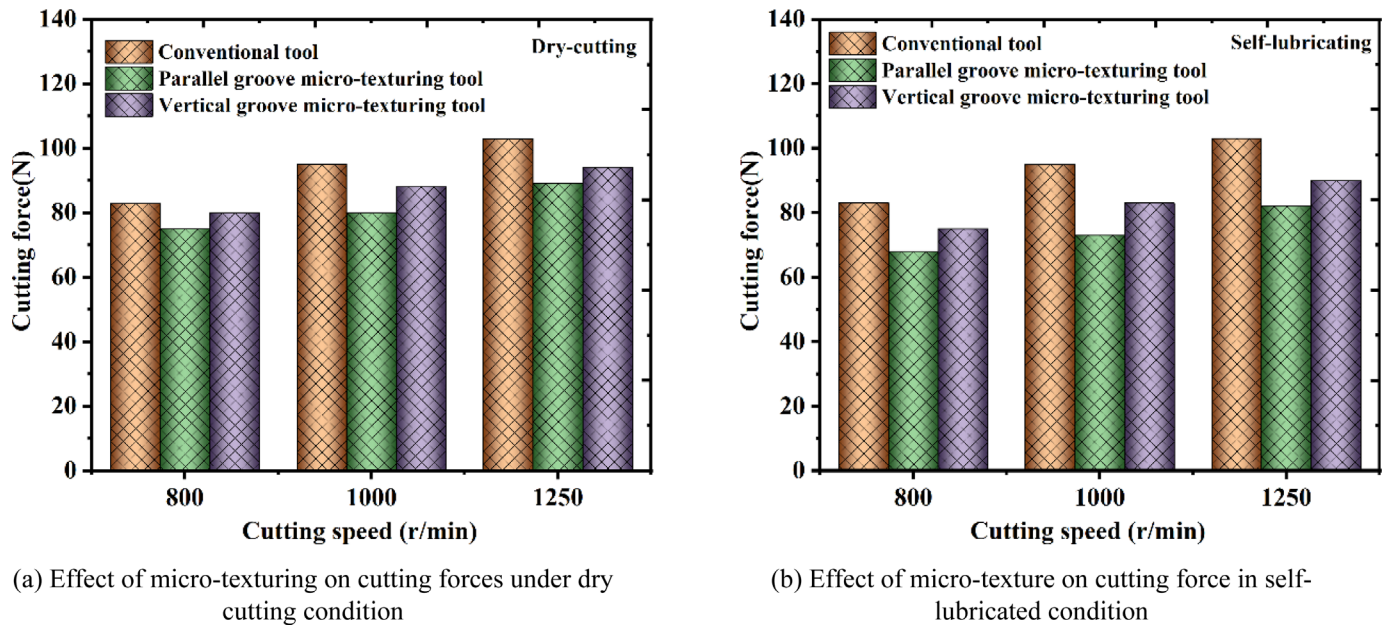


Fig. 12. Influence of lubrication status on cutting force.

the cutting area of the tool readily leads to the oxidation of molybdenum disulfide, necessitating the use of antimony trioxide (Sb_2O_3) as a flame retardant. The use of molybdenum disulfide powder in ongoing cutting machining processes can inhibit its oxidation [29,30].

Consequently, this document details the creation of two varieties of self-lubricating instruments, achieved by incorporating composite solid lubricants into both the parallel and vertical groove micro-textured structures. Concurrently, the setup includes the non-lubricated parallel groove micro-textured tool, vertical groove micro-textured tool, and the standard tool, all configured to perform the cutting test on aluminum alloy, adhering to these parameters: cutting speeds of 1250 r/min, 1000 r/min and 800 r/min, with a cutting back ap of 0.1 mm, and a feeding speed of 0.15 mm/r.

4.2 Experimental results and analysis

4.2.1 Influence of lubrication status on cutting force

The forces produced during the test were gathered and graphically represented, as depicted in Figure 14, illustrating how lubrication status influences cutting forces. Figure 12a illustrates that micro-texturing enhances cut reduction at an identical speed. As the cutting speed escalates, so does the cutting force, enhancing the cutting efficiency of the parallel groove micro-texturing tool, thus confirming the precision of the cutting simulation test. When sliced at a rate of 1250 r/min, tools for parallel and vertical groove micro-texturing achieved a 15.45% and 8.45% decrease in cutting power, respectively, in comparison to traditional tools.

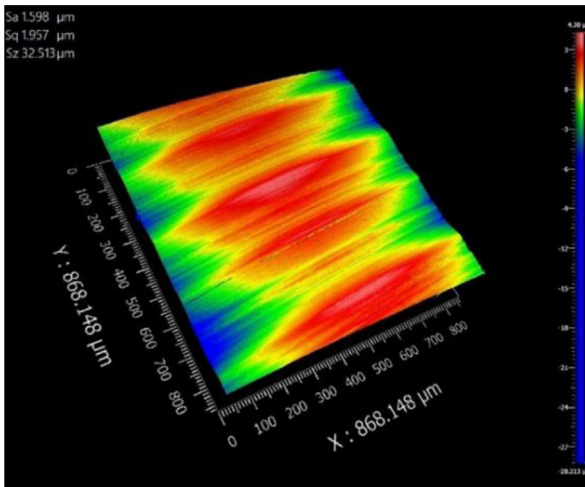
A comparative study of Figures 12a and 12b reveals that the pair of self-lubricating instruments are more effective in reducing cutting force compared to micro-textured tools. Included in these are the tools for self-lubricating parallel grooves and vertical grooves p At a

cutting velocity of 1250 revolutions per minute, the remote's cutting force diminishes by 20.39% and 12.62%, in contrast to the traditional tool. The reason lies in the solid lubricant's ability to completely saturate the micro-textured surface of the tool during processing, thereby creating a consistent lubrication layer on the tool's surface and minimizing direct metal-to-metal contact, r reduce wear on the surface of tools. Owing to the configuration of the tool's micro-texture in its operational zone, the segment of this micro-texture containing solid lubricant serves as a small container for storing lubricant and delivering oil to the cutting zone. Concurrently, the composite material's solid lubrication ensures consistent lubrication at elevated temperatures, and the tool surface's capacity to dissipate heat improves, aiding in lowering the cutting temperature an improving the efficiency of the tool.

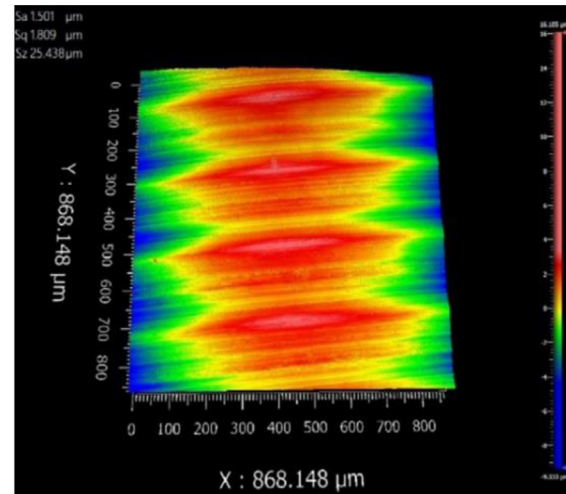
4.2.2 Influence of lubrication state on surface roughness

Measurements were taken of the aluminum alloy bars' surface post-cutting across various test groups, with Figure 13 illustrating the workpiece's surface structure post-cutting by two micro-textured tools at identical speeds and varying lubricates status of ions. The illustration reveals that the finished workpiece's surface texture of the non-lubricated micro-textured tool markedly exceeds that of the self-lubricated tool, with the self-lubricated parallel's surface roughness g The micro-textured tool of the roove measures merely 1.421 μm . In the case of the self-lubricated parallel groove tool, both the S_q 's surface roughness, representing the root-mean-square height, and the S_z 's maximum height, surpass the performance of other tools.

Data on the surface texture of the workpiece, processed at varying speeds, is gathered, and the impact of the lubrication condition on this texture is graphically represented in Figure 14. The figure illustrates that a

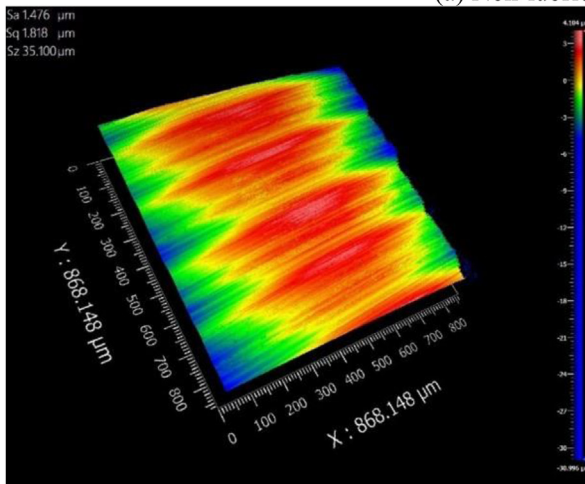


(i) 1000r/min Vertical groove micro-textured tool

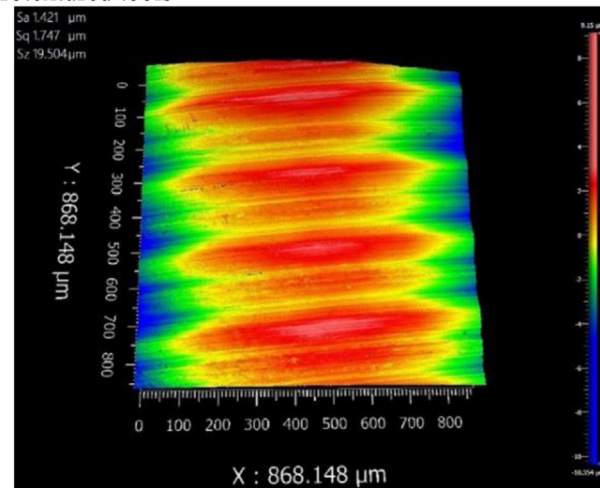


(ii) 1000r/min Parallel groove micro-textured tool

(a) Non-lubricated microtextured tools



(i) 1000r/min Vertical groove micro-textured tool



(ii) 1000r/min Parallel groove micro-textured tool

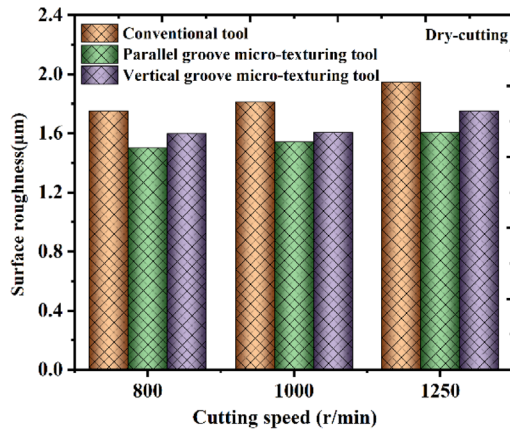
(b) Self-lubricating micro-textured tools

Fig. 13. Influence of lubrication state on the surface quality of workpiece after machining.

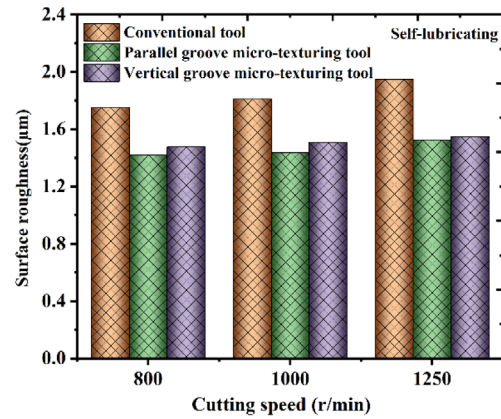
notable rise in the roughness of the cutting speed's surface is attributed to the intense deformation of the workpiece cutting layer material in high-speed cutting, known as the cutting force. As escalates, the steadiness of processing diminishes, leading to a reduction in the texture of the surface. Simultaneously, as the cutting speed accelerates and the production of tinier chips progresses, it becomes challenging to disperse along the tool's surface in time for accumulation, leading to a localized temperature difference on the tool's surface. As the chip shrinks, it becomes more pliable and adheres to the tool, impacting the quality of processing.

A comparative study of Figures 14a and 14b reveals that the self-lubricating parallel and vertical groove tools, in contrast to traditional tools, result in a reduction of surface roughness by 21.62% and 20.39% respectively at a cutti At a speed of 1250 r/min, the parallel and vertical groove micro-textured tools contribute to reducing surface roughness by 17.51% and 10.07%, respectively. The reason for this lies in the self-lubricating tool; during the initial

processing phase, the tool's surface is coated with a solid lubricant dispersion, and the cutting area of the tool surface is integrated into the workpiece's surface for slicing; this involves the tool body being cut by the heat-induced enlargement of the micro-textured segments in the solid lubricant extrusion process, this time a small amount of solid lubricant on the tool surface to form a lubricant film, this time the surface of the tool is in the lack of oil lubrication; processing of the late stage, with the generation of chips, more and more solid lubricant is "dragged" out of the micro-textured parts to form an oil film, this time the tool surface is in the lack of oil lubrication. Concurrently, in the case of parallel groove micro-textured instruments, the micro-texturing's orientation mirrors that of the chip's flow, facilitating easier chip outflow, with parallel groove micro-texturing encompassing a broader operational area. The surface area of the tool surpasses that of vertical groove micro-texturing, resulting in superior cutting efficiency compared to vertical groove micro-textured tools.



(a) Influence of micro-texture on surface roughness under dry cutting conditions



(b) Influence of micro-texture on surface roughness in the self-lubricated condition

Fig. 14. Effect of lubrication status on surface roughness.

4.2.3 Surface morphology of microtextured tools and chips

Observations of the tool surface morphologies after cutting were conducted, and Figure 15 depicts the surface morphologies of three types of tools. From the figure, it can be seen that all three tool surfaces exhibit varying degrees of damage. Among them, the traditional tool surface experiences the most severe wear, while the wear on the tool with parallel groove micro-textures is relatively minor. Additionally, cutting residues were observed on both the surfaces of the tools with parallel groove and vertical groove micro-textures. For micro-textured tools, during the initial stage of cutting, a small amount of debris enters and is stored within the micro-textures, while the majority of the chips flow out along the rake face of the tool. As the machining process progresses, a large amount of debris accumulates inside the micro-textures until they are filled, at which point the micro-textures become ineffective. In the later stages of machining, debris continuously adheres to the surface of the tool, causing cutting adhesion on the tool surface, which significantly impacts the quality of the machined product.

The chips produced during cutting were collected, and Figure 16 shows the morphology of the chips. From the figure, it can be seen that long chips are easily generated when cutting aluminum alloy materials, and during the experiment, it was observed that the chips wrap around the surface of the workpiece. Figure 16b reveals that the formed chips have burrs, which is due to the excessive shear stress applied to the cutting layer of the workpiece material during aluminum alloy cutting. Therefore, when cutting aluminum alloy, the cutting parameters should be reasonably selected to avoid the interference of long chips on the lubrication state of the tool surface and the stability of the machining process.

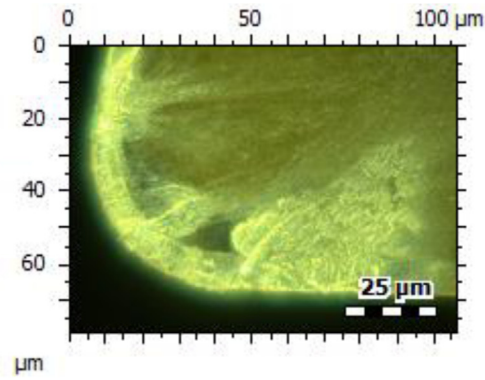
Based on the cutting experiments conducted with micro-textured tools under various cutting speeds and lubrication conditions, it can be concluded that micro-textured tools can contribute to a reduction in cutting forces and an improvement in the surface roughness of the workpiece after processing. Additionally, it was found that

adding solid lubricants to the micro-textures can further enhance the performance of the micro-textured tools, with the self-lubricating parallel groove tool exhibiting the best cutting performance.

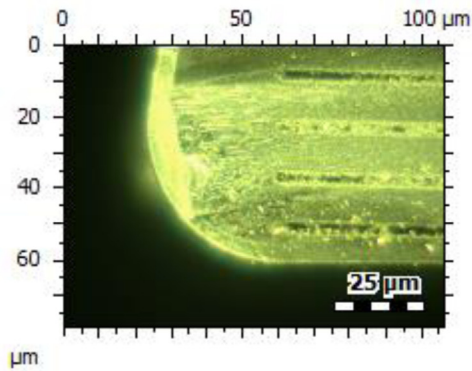
5 Conclusion

This research identifies through actual cutting experiments that issues such as high cutting forces, low machining accuracy, and chip winding frequently arise during the processing of aluminum alloy materials. Therefore, micro-textures are introduced onto the rake face of cutting tools to leverage their excellent friction-reducing and wear-resistant properties to optimize the cutting performance of the tools. The cutting performance of micro-textured tools is compared and analyzed through finite element simulation experiments and practical cutting tests with traditional tools. Furthermore, solid lubricants are filled into the micro-textures to further enhance the cutting performance of the tools. The research findings are as follows:

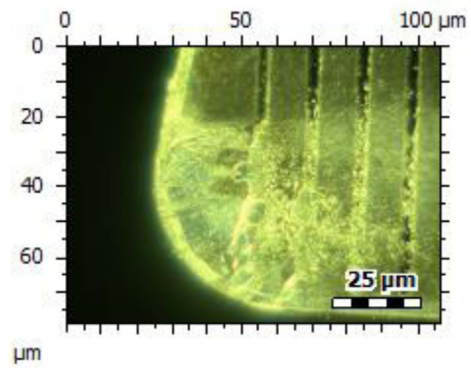
- According to the finite element simulation results for cutting aluminum alloy, micro-textured tools contribute to the reduction of cutting forces, stresses, and cutting temperatures. Specifically, the parallel groove micro-textured tool achieves a reduction of 20.69% in cutting forces, 23.84% in stresses, and 9.11% in cutting temperatures.
- Practical cutting experiments with aluminum alloy confirm that parallel groove and vertical groove micro-textured tools reduce cutting forces by 13.59% and 8.74% respectively, and surface roughness by 17.51% and 10.07% respectively. These findings validate the accuracy of the simulation results.
- By filling the micro-textures with solid lubricants, self-lubricating tools are created, further enhancing the cutting performance of the tools. In particular, the self-lubricating parallel groove micro-textured tool achieves a reduction of 20.39% in cutting forces and 21.62% in surface roughness.



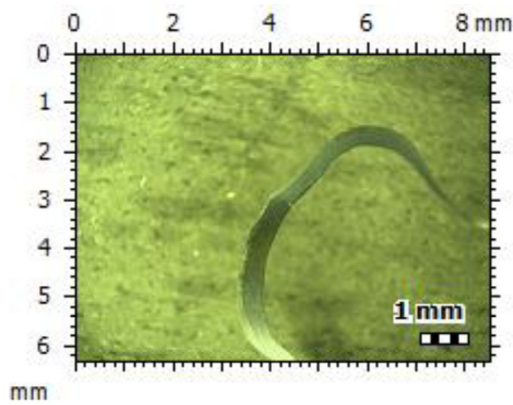
(a) Conventional tool surface morphology



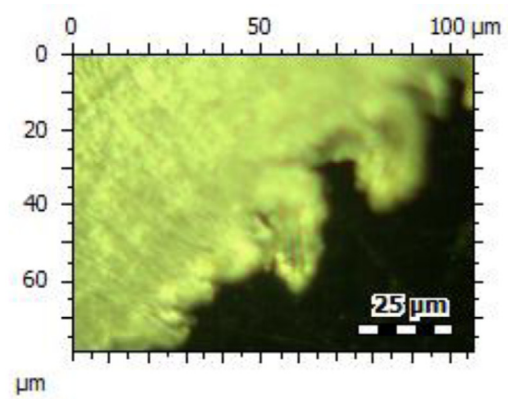
(b) Surface morphology of parallel-groove micro-textured tool



(c) Surface morphology of vertical-groove micro-textured tools

Fig. 15. Surface topography of 3 types of tools.

(a) Chip morphology of aluminum alloy



(b) Localized enlargement of aluminum alloy chip morphology.

Fig. 16. Chip shape.

– The novelty of combining micro-textured tools with solid lubricants lies not only in the design concept and technical implementation but also in performance optimization and the expansion of application fields.

This combination provides a new research method for optimizing tool performance and lays a theoretical foundation for subsequent research on self-lubricating tools.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

This paper has no associated data generated.

Author contribution statement

Tiantian Xu: Conceptualization, Methodology, Investigation, Writing; Jinpeng Liu: Resources, Supervision; Qingyu Guan: Investigation; Wanting Zhao: Validation; Chunlu Ma: Software, Data Curation, Formal Analysis.

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