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Enhancing Surgical Instrument Performance with Superhydrophobic Surfaces: Integrating 5-Axis CNC Milling and Laser Microstructuring

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Abstract: The research focuses on the development of surgical instruments with superhydrophobic surfaces using advanced manufacturing methods. Employing 5-axis CNC milling and laser microstructuring, the objective is to produce surgical tools with enhanced properties such as reduced fluid adhesion and increased antimicrobial effectiveness. The milling process provides precise control over geometry and surface finish, reducing the need for post-processing. Simultaneously, laser structuring facilitates the creation of micro- and nanostructures to achieve desired superhydrophobic and antimicrobial characteristics. Initial outcomes are anticipated to demonstrate significant improvements in performance, durability, and efficiency, leading to innovative medical tools that enhance surgical outcomes.

I. Introduction

Advancements in material science and surface engineering have opened up new possibilities for enhancing surgical instruments. One such advancement is the development of surgical tools with superhydrophobic surfaces, which significantly improve the performance and safety of these instruments. Superhydrophobic surfaces possess unique properties that make them ideal for medical applications, including reduced adhesion of bodily fluids like blood, easier cleaning and sterilization, and increased corrosion resistance [Huang et al., 2021; Shi et al., 2020]. This research focuses on developing a new generation of surgical instruments with superhydrophobic surfaces and the comprehensive process for their manufacturing, which includes mechanical fabrication and laser microstructuring [Lu et al., 2020; Sciancalepore et al., 2018]. Unlike conventional methods that require complex thermal treatments or coatings, this study aims to identify solutions that can achieve these superhydrophobic properties in a stable manner without the need for post-processing [Ngo et al., 2017; Khan et al., 2021]. Furthermore, the antimicrobial properties of these surfaces are also being investigated to add additional value to these new instruments [Yancheshme et al., 2021].

Given that the manufacturing of these components involves various machining steps, often performed traditionally or across multiple setups on different turning and milling machines, the resulting components typically require secondary manual finishing processes. These processes include manual deburring, surface quality enhancement, and fitting two parts together on fixtures with manual bending operations [Nyan et al., 2022]. Furthermore, significant costs and energy are expended on labor-intensive tasks to improve surface quality and ensure the functional performance of these assemblies after their assembly.

This research aims to leverage the capabilities of five-axis CNC milling to produce workpieces in a single setup, allowing the entire machining process to be completed with a single clamping [Sun et al., 2018]. By doing so, not only can we increase production efficiency and productivity, but we can also achieve better outcomes in terms of surface quality and geometric accuracy [Yancheshme et al., 2021]. By optimizing machining parameters and strategies, and carefully controlling tool entry and exit paths based on the chosen toolpath, these objectives can be met. Additionally, by utilizing appropriate clamping devices tailored to the extended length of the workpiece and paying careful attention to the sequence of machining operations, particularly considering the presence of a very thin section in the workpiece, the quality of the milling process can be significantly enhanced [Huang et al., 2021].

The primary motivation for this project is to enhance surgical instruments by creating surfaces that are better at remaining clean and reducing infection risks. The central hypothesis is that laser microstructuring can produce durable and effective superhydrophobic surfaces without the need for costly and complex post-processing methods [Lu et al., 2020; Shi et al., 2020]. This feature could help reduce costs and increase efficiency in surgical

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environments, as well as lower the contamination rates from microorganisms coming into contact with the instruments [Ngo et al., 2017; Sciancalepore et al., 2018].

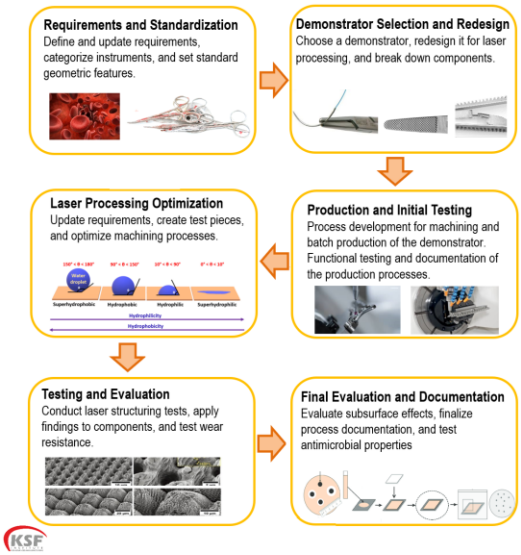

Figure 1: Overview of project scope and methodology

I.I. Multi-Axis Milling for Advanced Surgical Tools

Figure 1 provides an overview of the project's scope and the methodology used to conduct the research. In this project, multi-axis milling is employed as an advanced machining technique to optimize the manufacturing process and enhance the precision and quality of medical components. This method allows for the creation of complex geometries with high accuracy by using a five-axis CNC machine, which provides access to all angles of the workpiece and enables the production of intricate and precise surfaces. The final geometry of the components is carefully designed, and clamping fixtures are developed to ensure stability and accuracy during milling. The machining parameters, including spindle speed, feed rate, and cutting depth, are optimized to achieve the desired surface quality and dimensional accuracy. This approach not only improves the surface finish and reduces the need for additional finishing steps but also decreases production time and costs. Figure 2 illustrates the various challenges associated with maintaining surface quality during the milling process, highlighting the key factors that can affect the final surface finish.

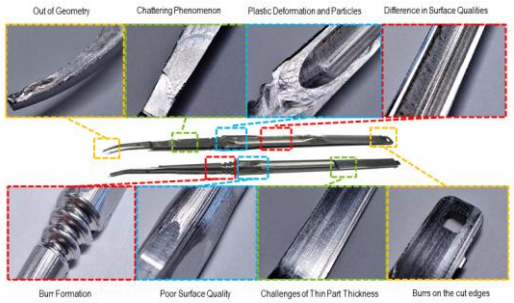

Figure 2: Surface quality challenges in milling

Moreover, the high precision of multi-axis milling enhances the reliability and durability of the manufactured components, which is crucial for surgical instruments that must withstand wear and corrosion. Figure 3 illustrates the optimization of NC (Numerical Control) programming and clamping techniques to enhance precision in five-axis milling.

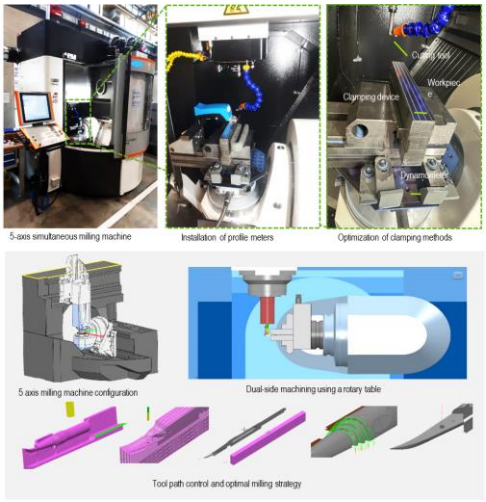

Figure 3: Optimizing NC Programming and Clamping for Precision in Five-Axis Milling

I.II. Laser Structuring for Advanced Surgical Tools

Laser structuring, on the other hand, is used to create micro- and nano-scale surface structures on metals and other materials, making it particularly useful for designing superhydrophobic surfaces and antimicrobial features in medical devices. In this process, various laser parameters, such as power, wavelength, pulse duration, and frequency, are carefully adjusted and optimized to achieve the desired surface characteristics, such as roughness, contact angle, and antimicrobial properties. This technique not only facilitates the development of superhydrophobic surfaces that prevent body fluids from adhering during surgeries, thereby improving visibility, but also enhances the antimicrobial properties of the surfaces, preventing microbial adhesion and growth. Additionally, laser structuring improves the wear and corrosion resistance of surgical instruments, extending their useful life. Both multi-axis milling and laser structuring focus on optimizing and advancing manufacturing processes to produce surgical tools with innovative features and superior performance, ultimately leading to increased precision, reduced costs, and improved functional characteristics. Figure 4 shows the samples prepared for setting laser parameters and testing for contamination, followed by subsequent structuring and laboratory analysis.

Figure 4: Prepared Samples for Laser Parameter Setting and Contamination Testing

II. Material and methods

The final geometries of the surgical instruments were designed using CAD software to ensure compatibility with the laser structuring process. Clamping fixtures for securing components during CNC machining were carefully designed for the 5-axis milling machine, focusing on minimizing machining vibrations and maintaining safe distances from tool holders. Milling parameters, including cutting strategies and tool paths, were optimized for efficiency and accuracy, especially in thin sections of the workpieces. Initial machining of pilot components was completed, and clamping fixtures were installed. CNC machining on a 5-axis milling machine achieved the finalized geometries, with parameters like feed rate, spindle speed, and cutting depth adjusted for desired surface finish and dimensional accuracy. The machining process was monitored for consistency and adherence to tolerances.

Samples were prepared for laser structuring, ensuring they were free from contaminants. Laser parameters, including wavelength, pulse duration, and energy density, were set to achieve the desired superhydrophobic properties. Some samples underwent hardening treatments to match the specifications for pincers. Laser microstructuring was performed to create micro- and nanostructures on the surfaces. Contamination testing will follow to verify the microstructures' integrity and effectiveness.

Post-laser structuring, the samples will undergo laboratory analyses:

- Structural Analysis: Using digital microscopy and scanning electron microscopy (SEM) to assess laser-induced microstructures.
- Contact Angle Measurement: Quantitative assessment of superhydrophobicity with a contact angle goniometer.
- Contamination Testing: Evaluating the impact of the superhydrophobic surface on microbial adherence.

Data from these analyses will validate the effectiveness of the laser structuring and ensure the superhydrophobic properties meet required standards. Contact angle and contamination test data will be analyzed for significance and consistency across samples.

III. Results

The planned next steps in this project include a comprehensive structural analysis using digital microscopy and SEM to assess the uniformity and quality of the laser-induced micro and nanostructures. Additionally, contact angle measurements will be conducted to evaluate the superhydrophobic properties of the surfaces, which are expected to demonstrate significant fluid repellency and reduced adhesion. Contamination testing is also scheduled to determine the effectiveness of these surfaces in minimizing microbial adherence, potentially enhancing their antimicrobial properties. Finally, further optimization of the 5-axis CNC milling process is anticipated to improve surface quality and geometric accuracy, reducing the need for manual finishing and increasing overall production efficiency. These planned analyses and optimizations will help validate the effectiveness of our approach in enhancing the performance of surgical instruments.

IV. Conclusions

This study outlines the groundwork for developing surgical instruments with superhydrophobic surfaces, aimed at enhancing performance, safety, and efficiency in medical applications. The proposed approach integrates advanced techniques, such as 5-axis CNC milling for precise manufacturing and laser microstructuring for creating surfaces with desirable properties. Although our research is ongoing, the anticipated outcomes include improved surface characteristics like reduced fluid adhesion and enhanced antimicrobial properties. Future work will focus on validating these expected benefits through rigorous testing and optimization of the manufacturing processes. The success of this project could lead to a new generation of surgical tools that offer superior functionality and durability, ultimately contributing to better clinical outcomes and reduced healthcare costs.

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