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Design an Ultrasonic Cutting Horn for Robotic Thermoplastic Trimming Applications

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ABSTRACT

This research presents the design and development of an ultrasonic cutting horn integrated with a robotic system for trimming Thermoplastic materials in automotive applications. The horn was designed using titanium alloy (Ti6Al4V) to achieve optimal mechanical strength, low mass, and superior acoustic properties. Finite Element Analysis (FEA) was conducted to ensure that the horn operated at the targeted frequency, resulting in a simulated resonance of 28.87 kHz. Experimental testing confirmed an actual operating frequency of 28.44 kHz, with a deviation of only 1.5%, indicating high model accuracy. The horn-blade assembly was mounted on an industrial robot for cutting trials, demonstrating smooth cut surfaces, clean edges, and reduced cutting resistance compared to conventional non-ultrasonic cutting. The results validate the feasibility and advantages of using ultrasonic energy for robotic TPO trimming, enabling precise, efficient, and high-quality cutting performance suitable for automotive manufacturing processes.

Keywords: ultrasonic cutting horn; ultrasonic cutting; robotic thermoplastic trimming applications

1. Introduction

1.1 The Importance and Origin of the Project

The emergence of Industry 4.0 and smart manufacturing has further emphasized the crucial role of robotics in the industrial sector. Many companies are increasingly integrating robotic solutions to enhance production efficiency, address labor shortages, and improve operational flexibility in rapidly changing global markets [1]. Furthermore, human–robot interaction plays a vital role as it enables seamless collaboration and communication between humans and robots, thereby enhancing both efficiency and effectiveness. In particular, robotic grasping and manipulation require the combined strengths of human intelligence and robotic capabilities [2].

Industrial robotic cutting has significantly contributed to improving manufacturing efficiency. With their high flexibility and wide working envelopes, industrial robots can process complex geometries more effectively than conventional machine tools [3]. However, robotic cutting remains a challenging control task, as it involves extensive physical interaction where robots must cope with unknown object mechanics and varying contact forces [4]. Moreover, these robots are required to operate with dexterity and safety in environments where humans and robots work collaboratively [5].

From a materials perspective, thermoplastics have been increasingly utilized in various industries such as biomedical, automotive, and electronics due to their outstanding physical and chemical properties [6]. In the automotive sector in particular, thermoplastics are extensively employed in the production of numerous components. However, the cutting process often encounters challenges such as blade breakage during manufacturing. Commercially available blades are commonly made of tungsten carbide, which, despite its high hardness, is inherently brittle, leading to recurrent failures at the same locations. Consequently, it is essential to analyze the underlying causes and establish effective solutions to enhance production efficiency.

Accuracy and surface finish are critical aspects in modern manufacturing industries, as the occurrence of unwanted burrs or irregularities can negatively affect assembly processes. An emerging method to reduce burr formation in metal cutting involves the use of ultrasonic vibrations, which introduce high-frequency oscillations [7]. Currently, ultrasonic technology has been developed to mitigate tool damage while improving the quality of the finished workpiece [8]. Ultrasonic-assisted cutting has proven effective in reducing vibration, thereby enhancing cutting performance in multiple dimensions, including cutting forces, tool wear, and the surface finish of the processed material.

2. Design of Ultrasonic Horns and Blades

2.1 Analysis of Relative Displacement Values of Points in the Ultrasonic Horn Structure for Cutting

In this study, a new horn design for an ultrasonic cutting system was developed, taking into consideration its suitability for integration with the cutting blade and efficient transmission of vibrational energy. Titanium was selected as the material for the horn due to its excellent mechanical and acoustic properties.

2.1.1 Calculation of ultrasonic horn power density

According to theoretical values, the power density range for the TPO (Thermoplastic Olefin) workpiece material lies between 3,000 and 5,000 W/kg.

Formula for calculating the weight of the horn:

$$\text{Horn Mass} = 350/(5{,}000)$$

$$= 0.07 \text{ kg. or } 70 \text{ g}$$

2.1.2 Calculation of horn length

For frequency matching, the horn must be designed to have a length corresponding to either half wavelength (½ λ) or quarter wavelength (¼ λ) of the ultrasonic sound wave. The selected material, titanium alloy (Ti6Al4V), has a sound velocity of 6,100 meters per second (m/s). Wavelength (λ) formula:

$$\lambda = 6{,}100/(28{,}500)$$

$$= 0.214 \text{ m. or } 214 \text{ mm}$$

From the calculations, the wavelength of the system was found to be 214 millimeters. According to the design principle, the researcher aims to set the horn length to half of the wavelength (λ/2). This design allows the system to operate at the fundamental mode frequency, which is the first natural mode characterized by high stability. Operating in this mode prevents mode hopping and is suitable for applications requiring high precision. Therefore, the designed horn length is 107 millimeters, as shown in Fig. 1.

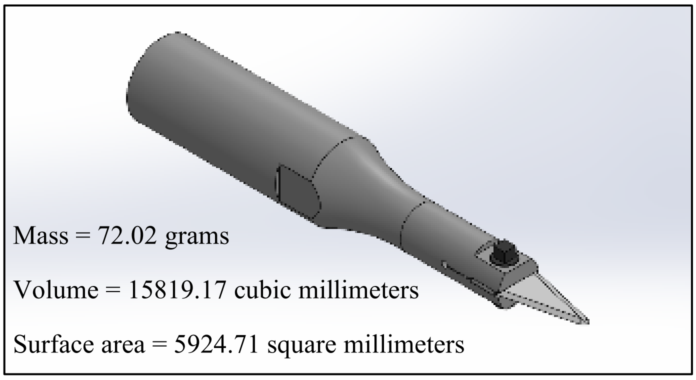

Fig. 1: Horn design and blade installation

The horn is manufactured from titanium alloy (Ti6Al4V), while the blade is made of steel (S50C). A frequency study was conducted using simulation software to perform finite element analysis (FEA) on the horn, blade, and the ultrasonic system combined with the transducer. This analysis aimed to investigate the mode shapes of vibration to verify whether the blade's vibration corresponded to that of the horn, and to check if the resonance frequency matched the ultrasonic system's operating frequency, as shown in Fig. 2.

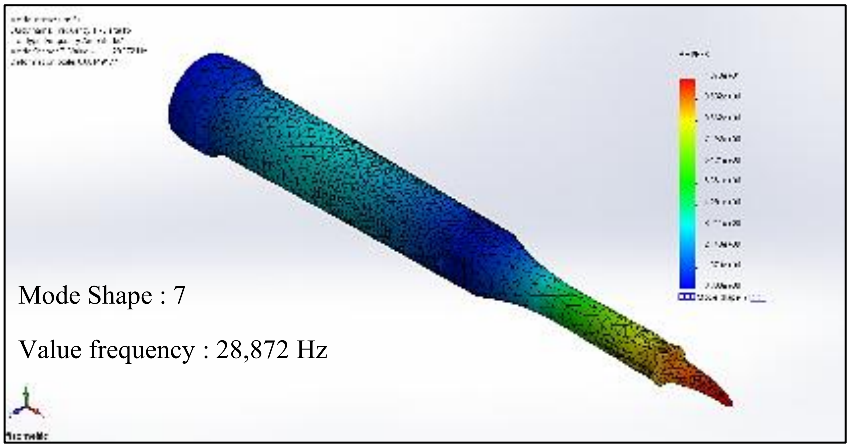

Fig. 2: The result of modal analysis on the transducer and the Horn-Blade assembly Mode7=Longitudinal / F=28,872 (Hz)

The analysis results indicated that the seventh resonance mode of the system exhibited a natural frequency of 28,872 Hz, which is close to the energy source frequency of 28,500 Hz, with a deviation of approximately 1.3%. This deviation falls within a range where the system can effectively achieve resonance. The resonance leads to a significant amplification of the vibration amplitude. The mode shape obtained from the simulation showed that the primary vibration occurs at the horn's tip, a critical location for transmitting shear force to the cutting blade. Therefore, it can be concluded that the system has the potential to efficiently transmit energy and operate compatibly with the energy source.

2.2 Design of the Blade to Work in Conjunction with the Horn

Designing the blade to function efficiently in conjunction with the horn is a critical step in the development of the ultrasonic cutting system. In this system, the blade not only serves as the component that contacts and cuts the material but also plays a vital role in receiving and converting the vibrational energy from the horn into precise and effective shear forces. This performance depends on the horn's characteristics, such as vibration frequency and amplitude size, which directly influence the blade's shape and dimensions.

Based on the data collected, the currently used cutting blade is manufactured from tungsten carbide with a thickness of 0.60 mm. This material exhibits high hardness but is inherently brittle, which often results in repeated fractures occurring at the same position, as shown in Fig. 3.

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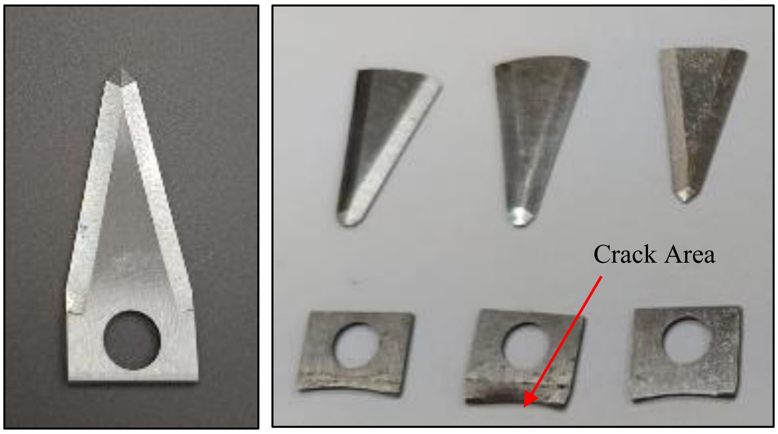

Fig. 3: Fracture of a conventional cutting blade without ultrasonic

To investigate the cutting force required for material shearing, experiments were conducted using a Compression Testing Machine to obtain mechanical parameters applicable for stress analysis through the Finite Element Method (FEM). A total of three test trials were performed to determine the average shearing force. The experimental results revealed that the average force required to shear and completely separate the material was 23.7147 N. This value will serve as a reference parameter for subsequent mechanical analysis and design processes, as shown in Fig. 4.

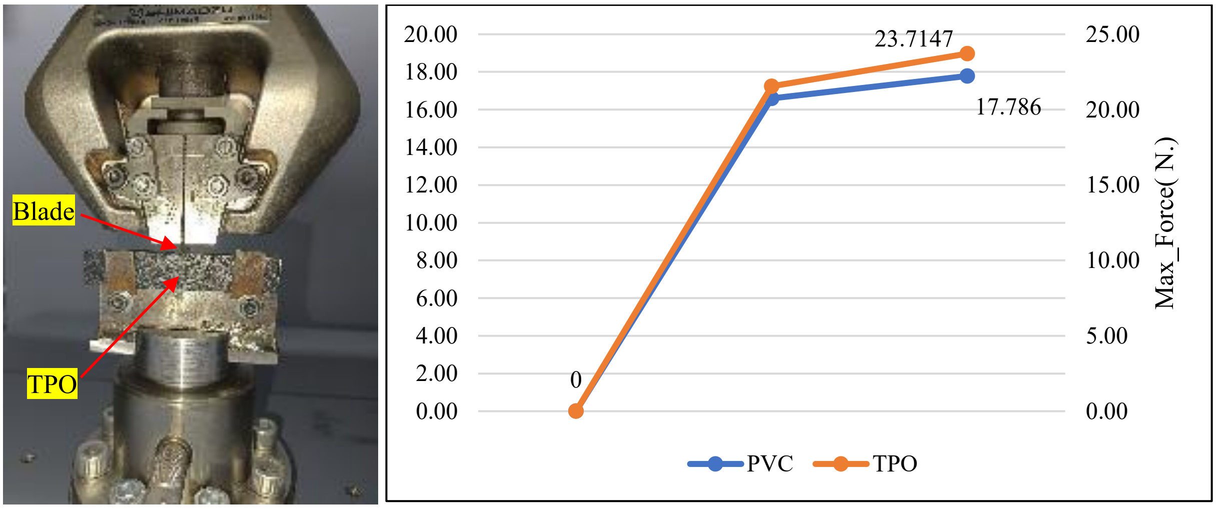

Fig. 4: Shear force testing

In this blade design, software was used to create a geometric model of the blade that is consistent with the pre-designed horn structure. Considerations were given to the connection points, the shape of the contact area, and the proper distribution of longitudinal vibration forces. These measures ensure that the blade can optimally receive and transmit energy from the horn, resulting in a cutting system that operates with high accuracy, speed, and extended service life.

The cutting force of the TPO material, obtained from experimental tests, was utilized to analyze and simulate the physical and engineering behavior of the system using the Finite Element Method (FEM) for stress analysis. In designing a new blade, the researcher selected SKH51 as the replacement material for the previously used tungsten carbide. The chosen material, SKH51, offers greater flexibility compared to the original blade material, which is expected to reduce recurrent fracture problems at the same positions and enhance the overall durability of the blade during operation.

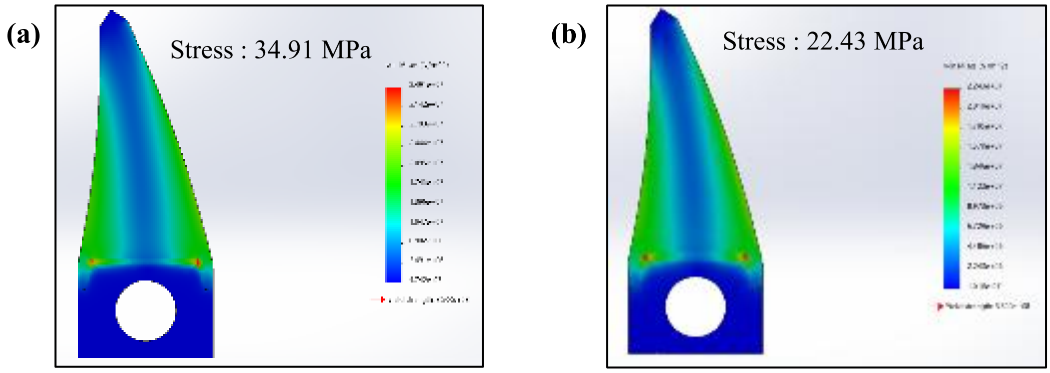

Fig. 5: Stress simulation, (a) conventional cutting blade thickness of 0.60 mm, and (b) new design cutting blade thickness of 1.00 mm

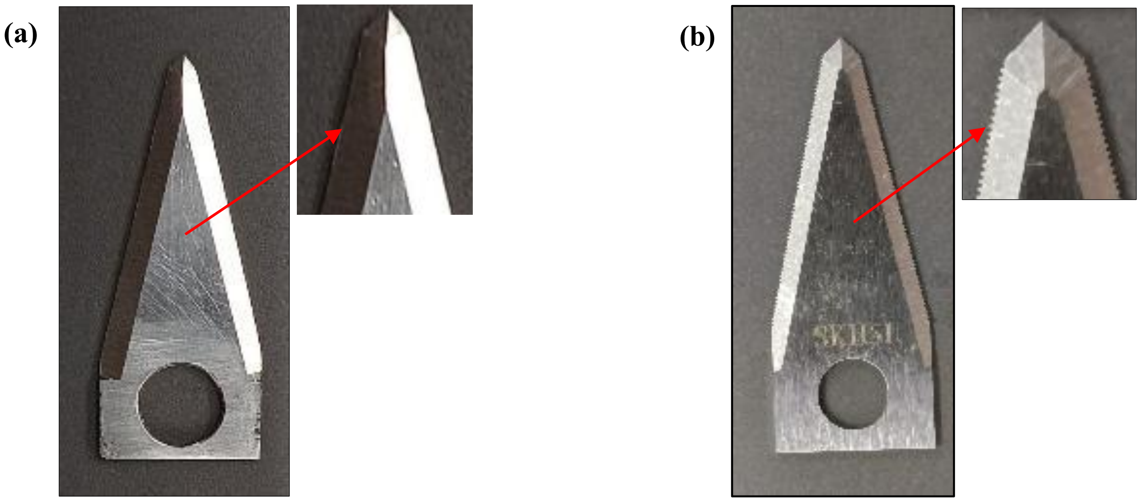

Fig. 6: Manufacture real blades, (a) conventional cutting blade thickness of 1 mm, and (b) new design Sawtooth cutting blade thickness of 1 mm.

It can be observed that as the blade thickness increases from 0.60 to 1.00 mm, the maximum stress generated within the material decreases significantly. This result is consistent with the principles of mechanics of materials, demonstrating the tendency that a thicker blade can distribute the applied load more effectively, thereby reducing localized stress, as shown in Fig. 5.

3. Experiment Setup

3.1 Experimental Method

Based on the analysis and finite element simulation, the components of the ultrasonic system, including the transducer and the horn tool, were manufactured using CNC machining to ensure precision and consistency with the designed model. These components were then assembled sequentially. The horn-tool assembly was mounted together with the transducer on a fixture, which was then installed onto an ABB robotic arm to perform tests in a controlled environment.

The materials selected for the experiments were TPO and PVC, which are thermoplastic materials commonly used in the automotive industry. The experiments were conducted in two modes: Ultrasonic Cutting and Non-Ultrasonic Cutting. The results were compared in terms of cutting efficiency, edge quality, and the resistance force encountered during the cutting process (Fig. 7).

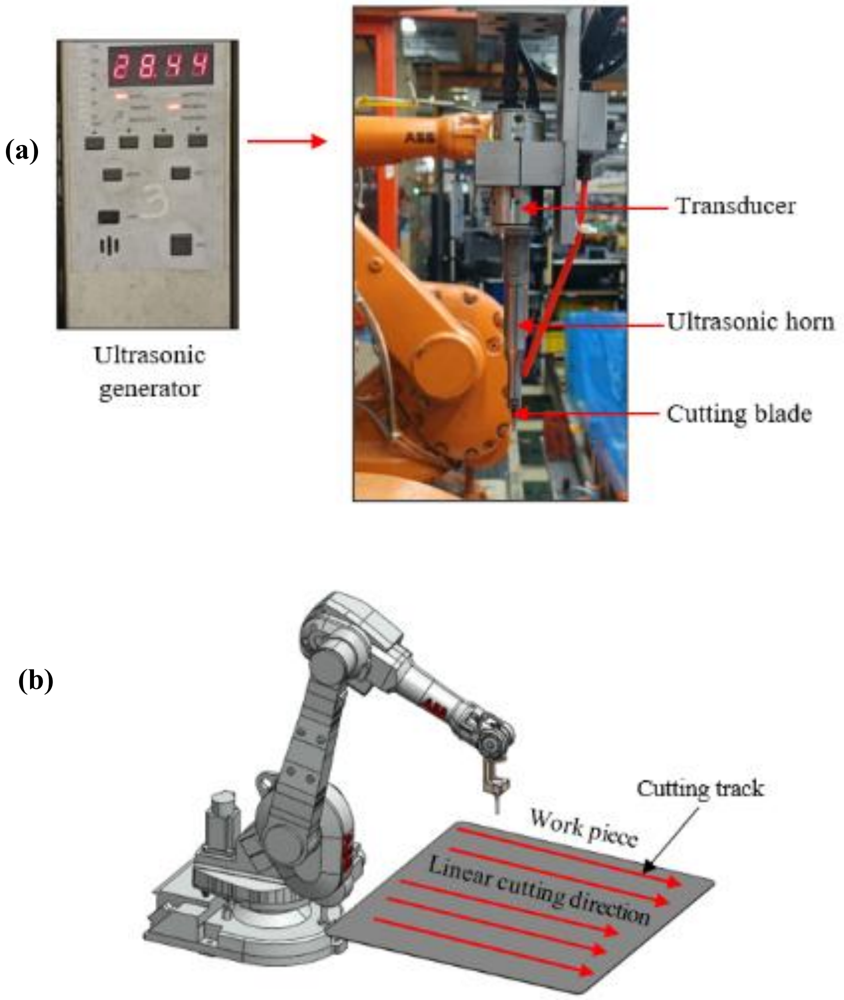

Fig. 7: Setting for cutting (a) installation of equipment for experimental operations, and (b) the apparatus.

Table 1: Parameters used in the experiment

Experimental parameters		
Fast to use cutting		0.3m/s
Cutting pattern		Linear cutting motion.
Work piece thickness		3 mm.
Frequency		28,440 Hz
Type Blade		1. Conventional cutting blade 0.60 mm. 2. Conventional cutting blade 1.00 mm. 3. Sawtooth cutting blad
Amplitude		95% (20µm zero-to-peak)
Number of experimental designs	Non-Ultrasonic	1. Conventional cutting blade 0.60mm.
		2. Conventional cutting blade 1mm.
		3.Sawtooth cutting blade 1mm.
	Ultrasonic	4. Conventional cutting blade 1mm.
		5. Sawtooth cutting blade 1mm.

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4. Results and Discussion

4.1 Compare the Distances Obtained from Cutting in Each Type of Experiment

Based on the results of the five experimental configurations, the most effective performance was achieved with the Sawtooth cutting blade (1 mm thickness) combined with ultrasonic cutting. This configuration enabled cutting distances of 655,776 meters for TPO material and 786,931 meters for PVC material. Conversely, the least effective performance was observed with the conventional cutting blade (0.60 mm thickness), which achieved cutting distances of only 25,920 meters for TPO and 31,104 meters for PVC, as shown in Fig. 8.

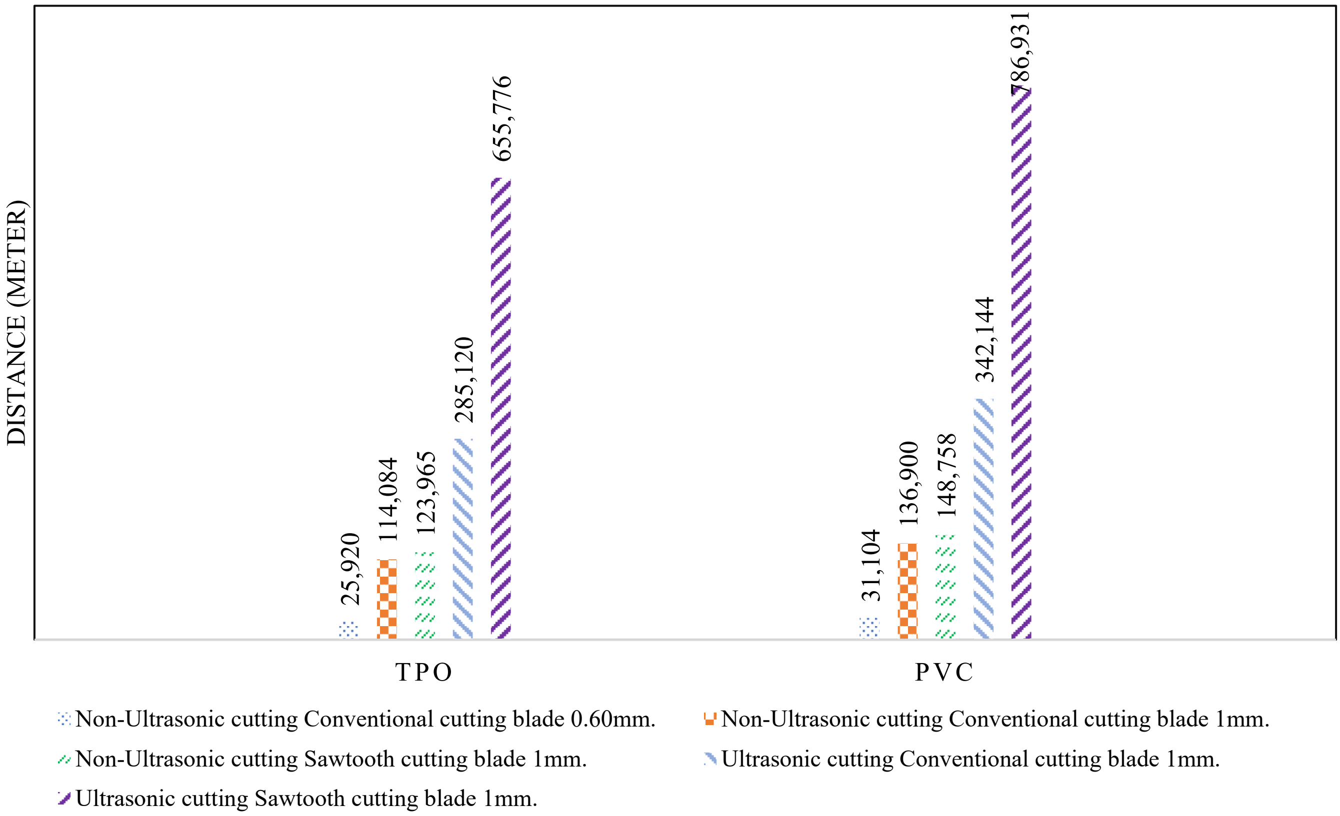

Fig. 8: Cutting Distance Comparison of Conventional and Ultrasonic Blades for TPO and PVC.

The practical testing of the ultrasonic cutting horn revealed that it was capable of operating at a frequency of 28.44 kHz, while the Finite Element Analysis (FEA) simulation predicted a resonance frequency of 28.87 kHz. This demonstrates a deviation of only approximately 1.5% between the simulated and actual operating frequencies, which is within an acceptable range. It indicates a high level of agreement between the simulation model and the real-world behavior of the system.

4.2 Surface Quality Comparison Results

Regarding the quality of the cut workpieces, surface inspections were conducted using a 3D laser microscope. It was found that the Ultrasonic Cutting mode produced superior surface quality. The cut surfaces were smooth, and the edges exhibited a slightly rounded and consistent profile, indicating uniform shear forces and reduced material tearing. In contrast, the Non-Ultrasonic Cutting mode yielded inferior quality, characterized by rough surfaces and visible scoring marks resulting from inconsistent mechanical force. This may be attributed to the higher resistance encountered during the cutting process, leading to uneven and less precise edge finishes. These experimental results confirm the

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advantages of ultrasonic cutting technology, both in terms of frequency accuracy and cutting quality, especially when applied to thermoplastic materials in the automotive industry.

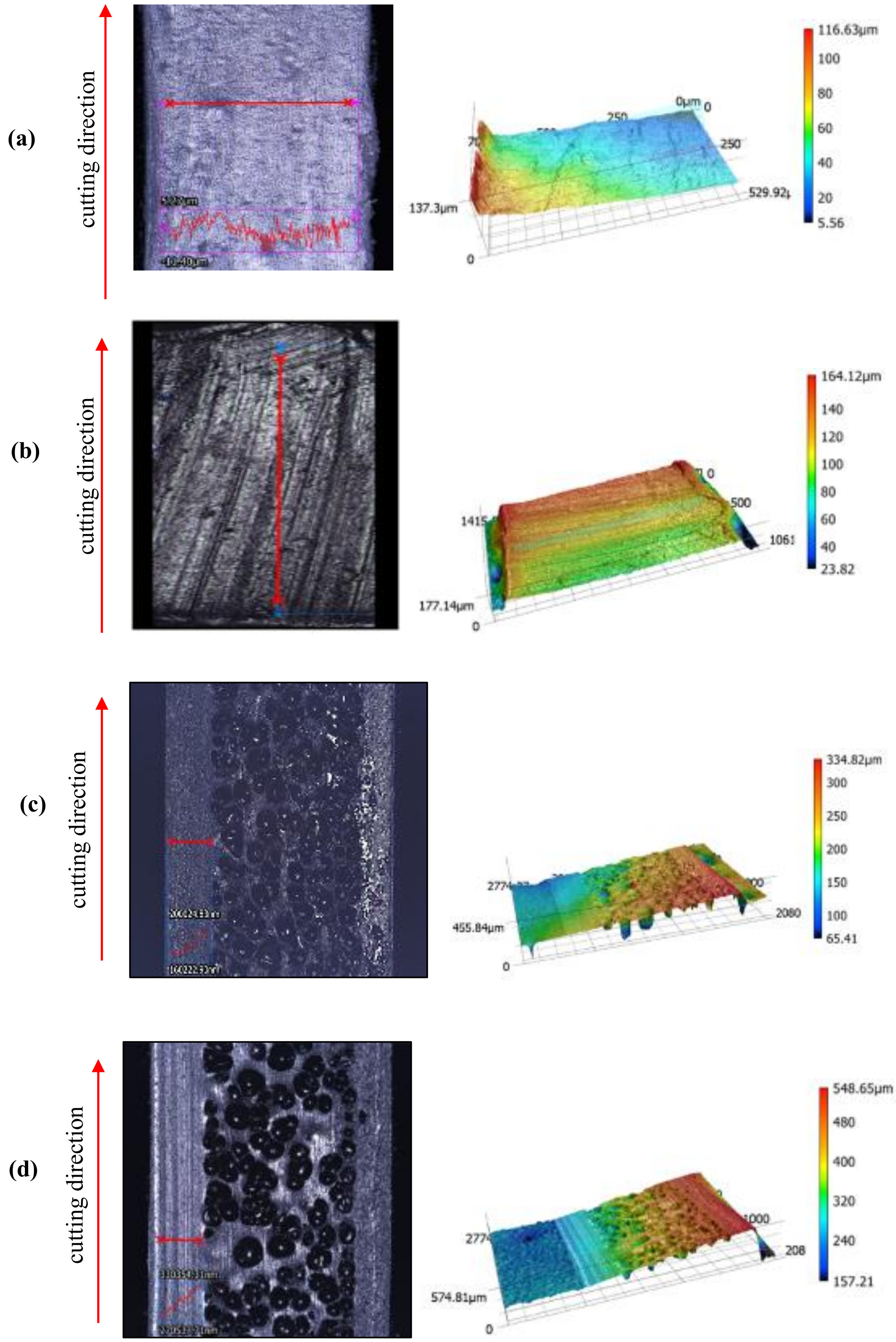

Fig. 9: Surface operates in two modes, (a) TPO Surface Sawtooth cutting blade by Ultrasonic Cutting, (b) TPO Surface Sawtooth cutting blade by Non-Ultrasonic Cutting, (c) PVC Surface Sawtooth cutting blade by Ultrasonic Cutting, and (d) PVC Surface Sawtooth cutting blade by Non-Ultrasonic Cutting

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Based on the experimental results and subsequent surface inspections conducted using a 3D laser microscope, it was observed that ultrasonic-assisted cutting markedly enhanced the surface quality of the workpieces. For TPO, the arithmetic average roughness (Ra) decreased from 2.23 to 1.59 µm, representing an improvement of approximately 28.7%. The average maximum height of the profile (Rz) showed a slight reduction from 16.12 to 16.00 µm, corresponding to an improvement of about 0.7%.

In the case of PVC, the improvements were more substantial. The Ra value decreased from 12.37 µm to 7.49 µm, indicating an improvement of approximately 39.4%. Similarly, the Rz value decreased from 55.67 µm to 35.55 µm, corresponding to an improvement of around 36.2%.

Workpieces obtained from the experiment using the Sawtooth knife edge (1 mm thickness), which exhibited the highest cutting performance, were analyzed for surface quality using a 3D Laser Microscope. The analysis revealed that ultrasonic cutting provided superior surface quality compared to non-ultrasonic cutting, as the latter left streaks and marks from the saw teeth on the workpiece surface.

Overall, these findings demonstrate that ultrasonic-assisted cutting significantly improves the surface finish of both TPO and PVC materials, with particularly pronounced benefits observed in the cutting of PVC.

Table 2: surface quality of workpieces, Arithmetic average roughness, and Average maximum height of profile

Measurement result			
Type of workpiece	Experimental type	Measurement value (µm)	
		Ra	Rz
TPO	Ultrasonic cutting	1.59	16.00
	Non-Ultrasonic cutting	2.23	16.12
PVC	Ultrasonic cutting	7.49	35.55
	Non-Ultrasonic cutting	12.37	55.67

5. Conclusion

The practical testing of the ultrasonic cutting horn demonstrated that the system operated at a frequency of 28.44 kHz, which is close to the resonance frequency obtained from Finite Element Analysis (FEA) simulation at 28.87 kHz. The difference of approximately 1.5% indicates the accuracy and consistency of the simulation model with the actual system behavior.

For the evaluation of cutting quality using a 3D laser microscope, it was found that the ultrasonic cutting mode produced smoother surfaces and clearly rounded edges, which were superior to the rough surfaces and visible scratches observed in the non-ultrasonic cutting mode. These experimental results confirm the advantages of ultrasonic technology in terms of both precision and cutting quality, particularly when applied to thermoplastic materials in the automotive industry.

The superior performance of the sawtooth blade is attributed to its small cutting area, which allows it to penetrate the workpiece more efficiently. Furthermore, the application of ultrasonic technology reduces the friction between the workpiece and the blade, resulting in lower stresses acting on the blade. This factor is crucial in extending the service life of the blade.

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