MALAYSIAN JOURNAL OF MICROSCOPY

Journal homepage: https://malaysianjournalofmicroscopy.org

RESEARCH ARTICLE

IMPACT OF VACUUM CLAMPING SYSTEM DESIGNS ON SURFACE QUALITY DURING THE END MILLING PROCESS

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Abstract. Traditional clamping systems often face challenges when securing thin materials, risking damage to the workpiece due to excessive force. In mass production, consistent and smooth processes are essential. Conventional clamping methods, such as top or side clamping, may interfere with the cutting tool's path or require additional safety measures. This study explores the application of a hybrid vacuum clamping system designed to securely hold acrylic plates during machining, focusing on depth and surface image analysis. A custom-designed vacuum block, available in two configurations—support airway and flat airway—was used to clamp a 160 × 160 × 6 mm acrylic plate. End milling with a 2 mm depth of cut (DOC) was performed, repeating the horizontal tool path seven times under varying pressure settings (-85 kPa to -25 kPa). Depth analysis was conducted using a Coordinate Measuring Machine (CMM), while surface images were captured via optical microscope. The findings indicate that the support block design provided better depth accuracy and surface quality, particularly at lower pressure settings, compared to the flat airway design. The results suggest that optimizing pressure settings and vacuum block design can enhance machining precision and workpiece surface integrity in thin material applications. A microscopic examination of the surface revealed that the vacuum clamping system effectively secured a 6 mm thick acrylic plate during the end milling process, at a pressure setting ranging from -85 to -45 kPa. This study provides valuable insights into improving vacuum clamping systems for efficient and accurate machining processes.

Keywords: End milling, optical image surface, vacuum clamping, acrylic plate, surface quality.

Article Info

Received 25 September 2024
Accepted 27 November 2024
Published 6 December 2024

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ISSN: 1823-7010, eISSN: 2600-7444

1. INTRODUCTION

The impact of vacuum clamping system designs on surface quality during the end milling process is a critical area of study in manufacturing and machining. Vacuum clamping systems are increasingly utilized in various machining operations due to their ability to securely hold workpieces without the need for mechanical fixtures. This method offers several advantages, including reduced setup time, improved accessibility for cutting tools, and enhanced surface quality of the machined parts [1]. In end milling, the quality of the surface finish is influenced by several factors, including the clamping method, cutting parameters, tool geometry, and material properties. Vacuum clamping systems provide a uniform distribution of holding force, which minimizes deformation of the workpiece during machining. This is particularly important for thin or delicate materials, where traditional clamping methods may induce stress and lead to surface imperfections [2]. Recent studies have shown that the design of vacuum clamping systems can significantly affect the surface quality achieved during end milling. Factors such as the design of the vacuum channels, the material of the clamping pads, and the overall configuration of the clamping system play crucial roles in determining the effectiveness of the vacuum hold and the resultant surface finish. For instance, optimized vacuum channel designs can enhance the suction force and improve the stability of the workpiece, leading to better surface quality [3]. Moreover, advancements in materials and technologies have led to the development of more efficient vacuum clamping systems. The integration of sensors and automation in these systems allows for real-time monitoring and adjustment of clamping forces, further enhancing the machining process's precision and reliability [4]. The vacuum clamping system features a new design of the vacuum block used as clamper on both sides [5-6]. Through the research is to aims an application of hybrid vacuum clamping system to an acrylic plate during machining in order to observe the image surface of the workpiece.

A conventional clamp is unable to clamp thin material, whereby excess forces can lead to a marked defect on the workpiece surfaces. A mass-produced product will go through repeated processes; therefore, it is important to have an efficient flow process [7-9]. Using conventional clamping requires placing and continuous clamping. Top surface workpiece clamping limits the cutting tool path area during machining, and moreover, clamping from the side may lead to the first issue and additional protection may be required [10]. The vacuum clamping system is capable to solve the problems, whereby it can clamp various thicknesses, do not leave a mark when clamping, easy re-clamped method, and vacuum suction only on the bottom side of the workpiece. After the engraving process, the effect of the machining will be observed on the image's surface [11].

The process of end milling is used to manufacture profile recesses and deep slots in aerospace, and automotive industries. End mill is one of the most widely used multipoint cutting tools that is essential in many industries, such as aerospace, shipbuilding, and automotive for the machining of various complex components [12-13]. The quality of the production process impacts the production time, costs, and waste effects of defective parts. The higher production performance depends on improving the efficiency of the manufacturing process by reducing waste from rejected. Important process parameters reduce depth, speed, and feed to minimize process defect and optimize the process during the cutting process [14]. These parameters affect the workpiece surface quality. Other factors, such as cutting tool condition and machine condition may also affect the quality of surfaces, but the selected parameter is a major parameter that needs to be cautioned [15]. The most critical parameter influencing the cutting forces was found in the cutting depth. Vibrations in milling interrupt performance, and excess vibrations increase tool wear, chipping tools, resulting in poor surface finish [16-17]. Developing new prototype or concept vacuum clamping requires to evaluate the performance machining. Therefore, this research aims to apply a hybrid vacuum clamping system to an acrylic plate during machining in order to observe the image surface of the workpiece.

Figure 1 show the prototype of vacuum clamping system that focus on the flow circuit and components [11-12]. Major components of the system are the reservoir and vacuum pump. Bigger reservoir tank, able to hold high pressure longer, and powerful vacuum pump can hold up to maximum -95 kPa pressure of suction. The system was designed in a parallel circuit, whereby it could split into two slots of the vacuum inlet from vacuum pump into A and B distributor. It is simply used to clamp multiple or larger workpieces.

Clamping involves securely holding the workpiece in place, with each clamping device chosen and positioned on the work holder for optimal performance. Vacuum clamping is a cost-effective option due to its short setup time and the ability to machine the workpiece on all sides. Individual suction plates can be easily removed and reinstalled without the need to replace the entire system.

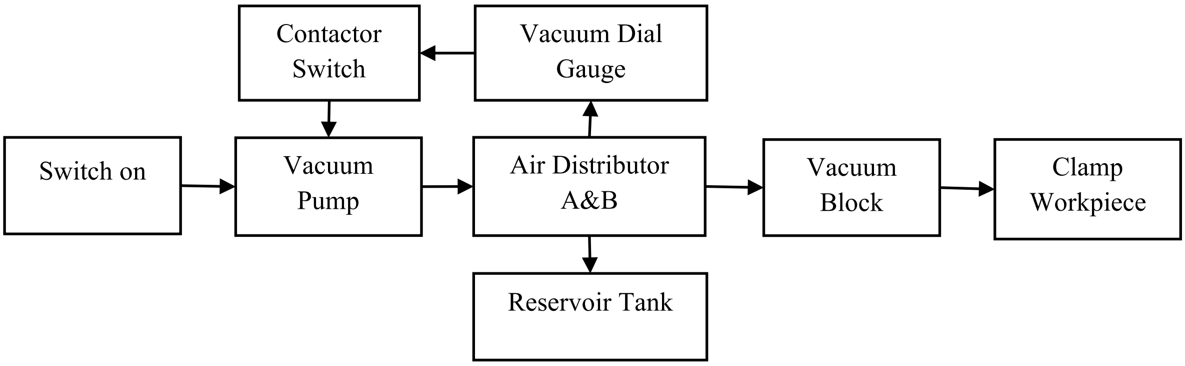


Figure 1: Vacuum Clamper System

2. MATERIALS AND METHODS

2.1 Vacuum Block

The vacuum block plays a significant function, which is the mechanism to clamp the workpiece in place. Reviewing patent design and industrial concept from [13,16] led to the conclusion that there were two styles of airway design for a single vacuum block: Support and flat airway design (Figure 2). The vacuum block is dual suction, which means it can clamp on any flat surface, regardless of the material or surface. The support airway design has slotted engrave of 4 mm depth, leave it with 4 × 4 pillar squares with gap of 10 mm. The flat airway design has flat surface with 4 mm depth. The area of suction pressure is 130 × 130 mm is sealed with rubber sealant around the area with width 10 mm and 4.2 mm thickness to avoid pressure leaking.

(a) Support design (b) Flat design

Figure 2: (a) Support design (b) Flat, design of vacuum block

2.2 Workpiece Material

The hybrid vacuum clamping system can clamp thin workpieces. Non-metal workpieces cannot be magnetized. Poly (methyl methacrylate) or PMMA is a transparent engineering material. A 160 × 160 mm with 6 mm thickness acrylic plate was used for the experiment.

2.3 Experiment Setup

In this experiment, the main factor was that the workpiece will undergoes engraving proses seven times when each clamping process perform on different levels of pressure setting from -25 kPa to -85 kPa increase by 10 kPa horizontally. The engrave process was subsequently selected for 2.0 mm depth of cut. With the machining cutting parameter spindle speed 9500 rpm and feed rate 1800 mm/min, roughing cutting depth of cut at 1.9 mm was conducted and left with 0.1 mm. The process steps were repeated with each line to give a gap for pressure level setting to change, while pausing during machining.

2.4 Depth Analysis

After the workpiece machining, the workpiece was taken to a CMM for depth analysis inspection. Using Zeiss Contura CMM to measure the depth of cut after machining. The 160 × 160 mm acrylic plate horizontally divided into 5 points and 7 level pressure verticals. At each point need to set base plane and depth plane for the CMM to measure the dimension.

2.5 Microscope Image Surface

Figure 3 shows the surface and edges of an acrylic plate were captured after the end milling machining process was completed to observe the effect of cutting with various clamping pressure settings ranging from -85 kPa to -25 kPa. In this observation are using Nikon SMZ 745T microscopes, are well-suited for both industrial and biomedical applications because to its 7.5× zoom magnification and 115 mm working distance. A HDMI camera is attached to the microscope view in order to display the image on a computer monitor.

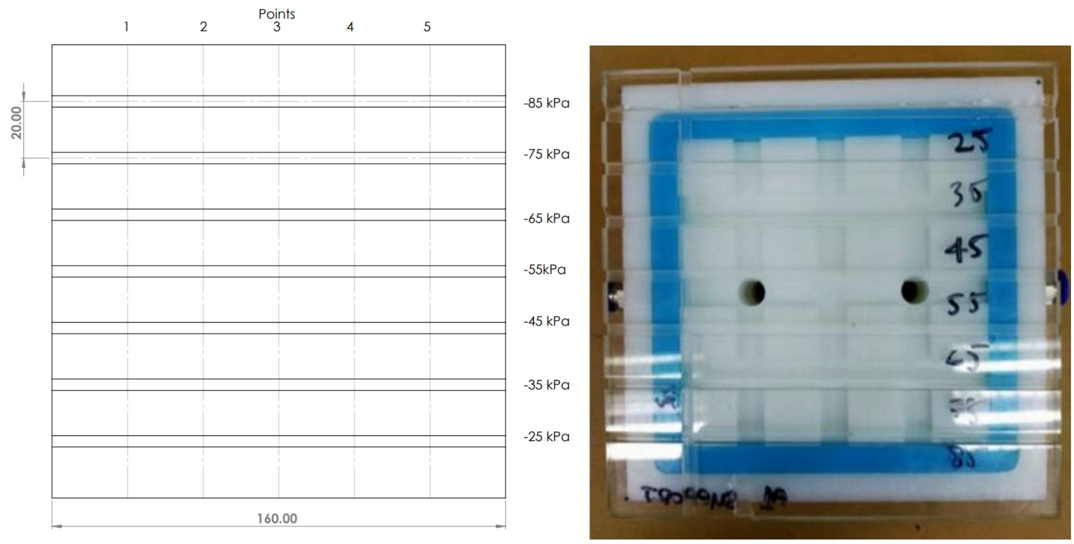


Figure 3: Position of coordinate point for acrylic plates

In this observational test, an acrylic plate was clamped using a single vacuum block. The surface images were captured at the inlet and outlet along the left-to-right cutting tool path. Seven pressure settings were repeated on each of the two acrylic support plates and flat airway vacuum block clamping design. Finding the relationship between the cutting parameter and the level of clamping pressure.

3. RESULTS AND DISCUSSION

3.1 Depth Analysis

Figure 4 illustrates the Depth of Cut (DOC) graph for the single vacuum block clamping system. The results indicate that the Support airway design vacuum block performs within the tolerance range of ±0.5 mm, showcasing its superiority in maintaining dimensional accuracy. At higher pressure settings (-85 to -45 kPa), the DOC on both support and flat vacuum blocks remains below 2 mm, signaling an undercut condition. However, the Flat vacuum block exhibits a shallower DOC range (0.5>DOC>1.5 mm) under the same pressure settings, which fails to meet the required tolerance. At lower pressure settings (-45 to -25 kPa), both vacuum blocks tend to have greater DOC values, but the Support airway design achieves a fully green region (1.5>DOC>2.5 mm), indicating optimal performance.

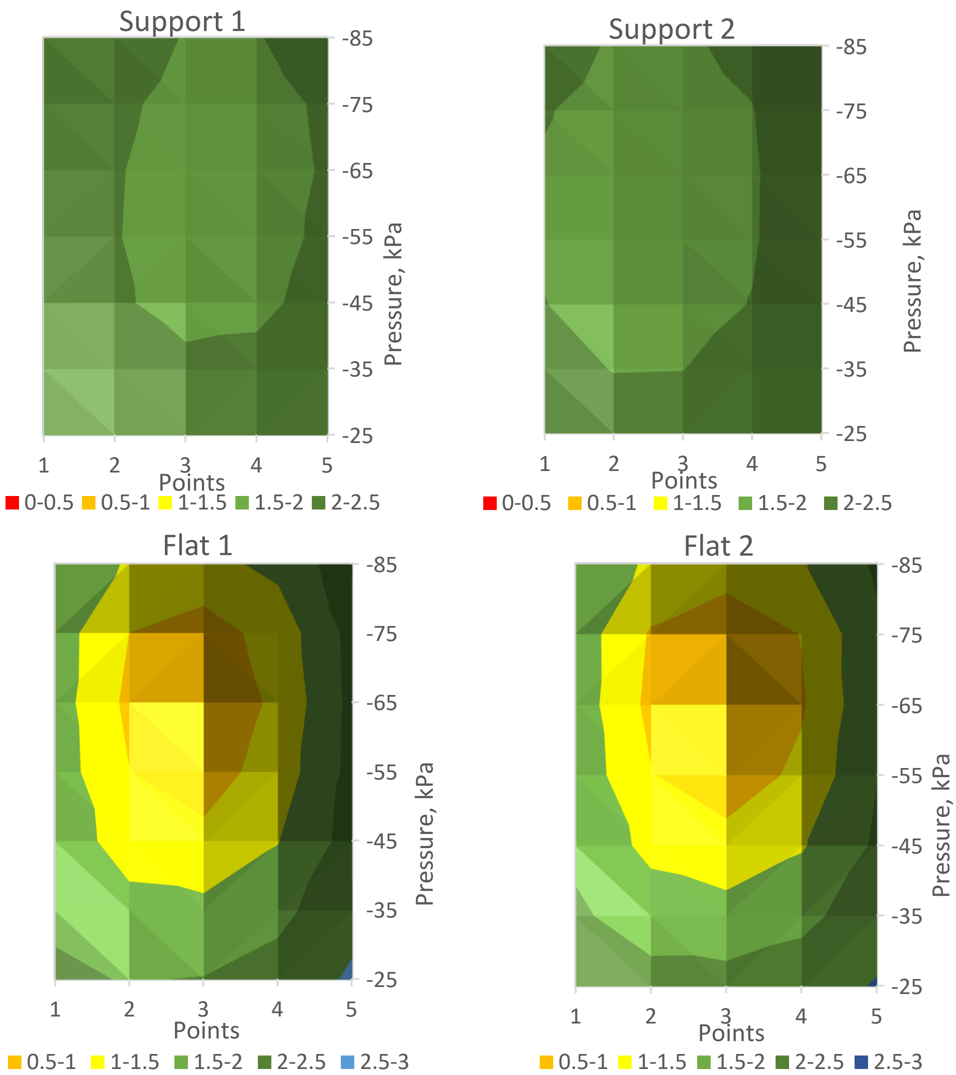


Figure 4: Surface graph of DOC when using vacuum clamping block

The influence of machining parameters such as feed rate, spindle speed, and depth of cut (DOC) plays a critical role in surface quality. According to [15], optimizing these parameters reduces surface roughness, ensuring smoother finishes and better edge quality. For instance, increasing spindle speed can minimize vibration-induced irregularities while simultaneously enhancing the thermal softening of materials like PMMA, allowing for cleaner cuts. Similarly, reducing the feed rate at lower clamping pressures can alleviate stress-induced surface imperfections, a technique also supported by [17], who demonstrated its effectiveness in ultrasonic vibration-assisted milling processes.

Furthermore, [18] emphasized that the interaction of cutting parameters with workpiece material significantly influences surface integrity. Their study on aluminum alloys highlighted that a balanced combination of feed rate and spindle speed prevents excessive tool wear and promotes consistent surface texture [18]. These insights align with the present findings, underscoring that optimizing machining parameters is essential for achieving high-quality surface finishes, particularly when machining thin materials under varying clamping pressures. Consequently, the integration of controlled vacuum clamping with optimized cutting parameters ensures better dimensional accuracy and surface quality in end milling processes.

3.2 Image Surface

The analysis of the image surfaces of the end-milled acrylic plates, captured under a microscope, provides significant insights into the performance of the Support and Flat single vacuum block designs. Table 1 shows that the Support vacuum block design achieves smooth surfaces and well-defined edges across pressure settings ranging from -85 kPa to -35 kPa. Similarly, Table 2 reveals that the Flat vacuum block design maintains smooth surfaces and edges at pressure settings from -85 kPa to -45 kPa. However, differences between the two designs become more evident at lower pressure settings, where the Support airway design outperforms the Flat design.

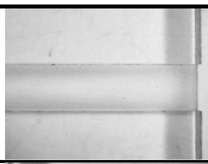
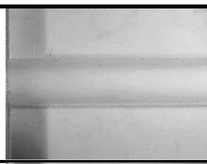
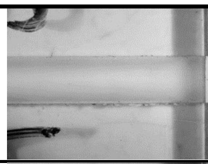
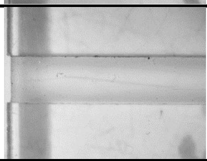
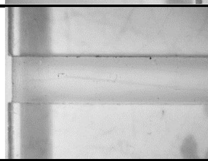
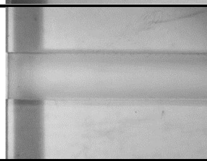
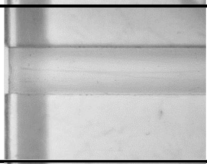
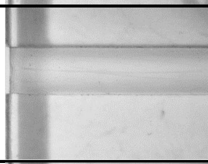
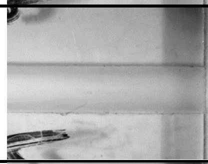
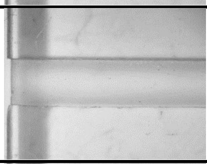
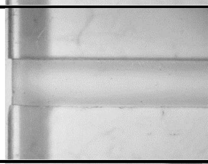
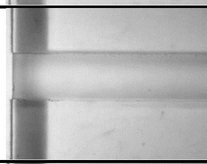
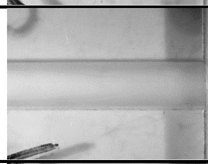
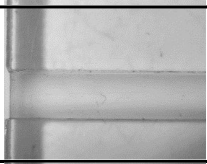
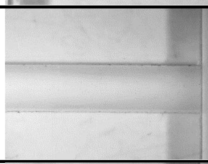
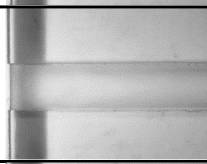
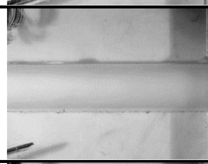
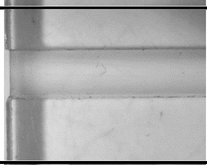
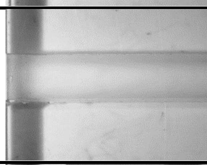
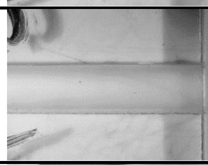
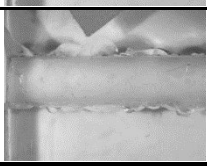
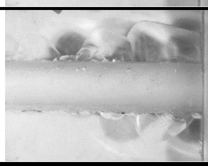
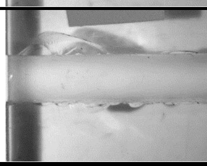
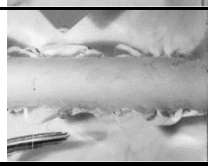
The critical observation is that the Support airway design maintains smooth surface characteristics down to a minimum pressure of -35 kPa. At this threshold, surface imperfections begin to appear, such as slight roughness and chipped edges. In contrast, the Flat vacuum block design demonstrates smooth surfaces only down to -45 kPa, with visible roughness and edge chipping below this threshold. These findings align with [18], who emphasized that inadequate clamping forces often lead to micro-deformations and stress concentrations, resulting in compromised surface quality during machining.

At higher pressure settings (-85 kPa to -45 kPa), both vacuum block designs show excellent surface quality with smooth edges and minimal defects. This outcome can be attributed to the sufficient clamping forces provided at these pressures, which effectively suppress vibrations and maintain workpiece stability during the machining process. [19] highlighted, higher clamping forces minimize relative motion between the workpiece and the tool, thus enhancing surface finish.

At lower pressure settings (-35 kPa to -25 kPa), the weaker clamping forces are insufficient to counteract the vibrations generated during machining. This results in surface roughness and chipped edges, particularly for the Flat vacuum block design. The Support airway design, with its enhanced vacuum channel configuration, demonstrates better performance by providing more uniform clamping forces. [5] noted that advanced vacuum channel designs, such as the Support airway's slotted engravings, ensure more stable suction and improve surface quality under reduced clamping forces.

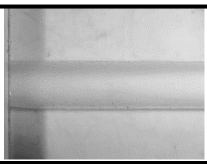
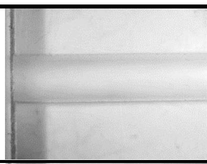
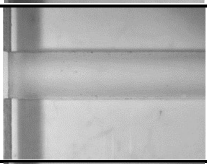
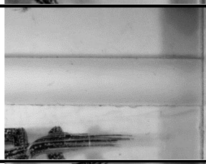
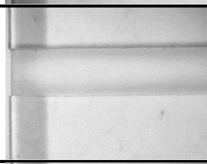
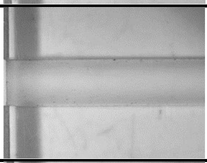
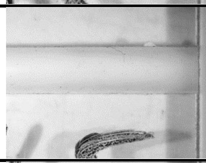
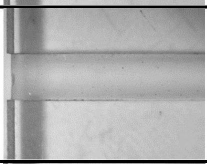
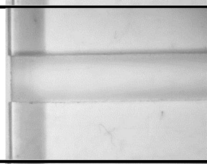
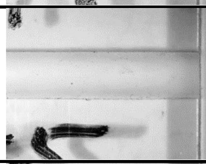
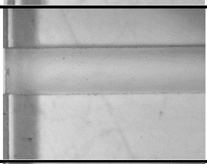
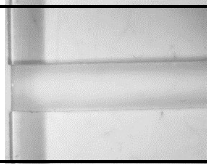
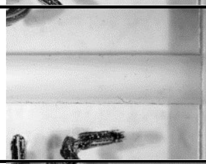
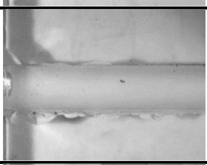
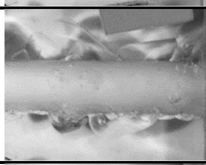
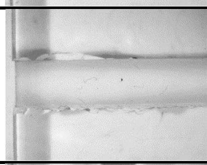
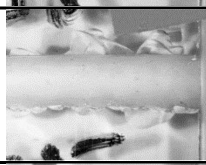
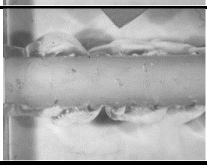
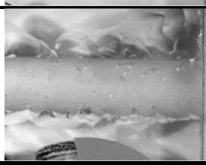
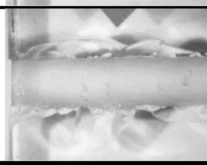
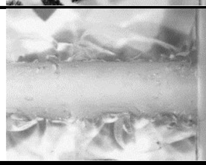
The microscopic examination of the surfaces reveals that machining-induced flaws, such as tool marks and edge chipping, are more prevalent in the Flat vacuum block design at lower pressure settings. These defects can compromise the functionality and aesthetic appeal of machined components. [20] highlighted the importance of maintaining consistent clamping forces to prevent such defects, especially when working with thin or delicate materials.

Table 1: Image surface for support vacuum block design

Presssure (kPa)	Support plate 1 (160 × 160 × 6 mm)		Support plate 2 (160 × 160 × 6 mm)	
	Inlet	**Outlet**	**Inlet**	**Outlet**
-85				
-75				
-65				
-55				
-45				
-35				
-25				

The image surface analysis clearly demonstrates that the Support airway design vacuum block is more effective in maintaining surface quality across a wider range of pressure settings compared to the Flat design. This superiority is particularly evident at lower pressures, where the Support design continues to deliver better surface finishes and edge quality. These findings underscore the importance of optimizing vacuum block designs and clamping forces to achieve high-quality machining outcomes. Future work could explore the integration of dynamic clamping systems with real-time monitoring to further enhance machining precision and surface integrity.

Table 2: Image surface for flat vacuum block design

Presssure (kPa)	Flat 1 (160 × 160 × 6 mm)		Flat 2 (160 × 160 × 6 mm)	
	Inlet	Outlet	Inlet	Outlet
-85				
-75				
-65				
-55				
-45				
-35				
-25				

3.3 Comparison Data 3D Surface Between Support and Flat In Multi Vacuum Blocks

A comparative analysis of Coordinate Measuring Machine (CMM) results highlights the superiority of the Support vacuum block design over the Flat vacuum block in maintaining dimensional tolerances during the end milling process. The Support vacuum block consistently exhibited greater stability across all three measured positions, resulting in fewer off-tolerance deviations. In contrast, the Flat vacuum block demonstrated significant off-tolerance results, particularly in the center of the block, due to the undercut phenomenon.

The Support vacuum block achieved a depth of cut with no undercut values, maintaining consistent tolerances within the acceptable range of 1.5 to 2.5 mm, as indicated by the green region in Figure 5. However, at the inlet and outlet, minor deviations below 1.5 mm were observed, representing undercut values. These deviations were minimal compared to the Flat vacuum block, which displayed extensive undercutting at the center, attributed to higher suction pressures. The increased pressure caused the workpiece to warp beyond the flexibility threshold, resulting in depth of cut variations outside the acceptable tolerance range.

The surface chart in Figure 5 illustrates the data, with overcut values (2.5 to 5.5 mm) depicted in yellow to dark red regions and undercut values (0.0 to 1.5 mm) shown in blue. The Flat vacuum block's inability to maintain even suction pressure across its surface led to pronounced warping and undercut values, particularly at the center. Conversely, the Support vacuum block's distributed airway design effectively minimized these effects, offering greater stability and precision in the milling process.

These findings underscore the critical role of vacuum block design in achieving dimensional accuracy and surface quality. Future studies could explore optimizing suction distribution to further mitigate undercut and overcut effects, enhancing machining outcomes for diverse applications.

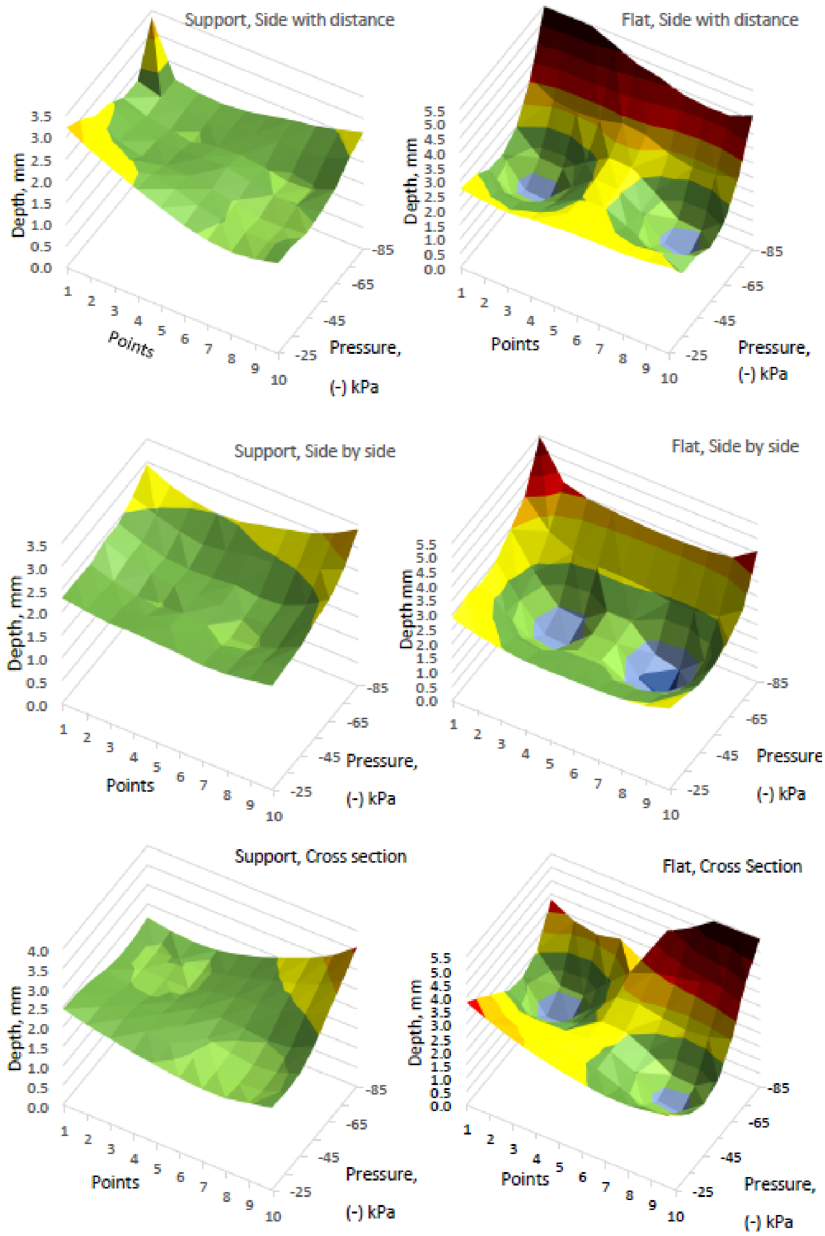


Figure 5: CMM result on depth analysis with 3D surface chart

4. CONCLUSIONS

This study evaluated the performance of Support and Flat airway design vacuum blocks in a hybrid vacuum clamping system for machining processes. The Support airway design consistently outperformed the Flat design, particularly at lower pressure settings, ensuring dimensional accuracy and surface quality. It maintained a depth of cut (DOC) within the acceptable range of 1.5 > DOC > 2.5 mm, even at pressures as low as -25 kPa, demonstrating superior clamping ability and resistance to deformation. In contrast, the Flat vacuum block often failed to meet tolerance requirements at lower pressures due to a hollow center, leading to workpiece warping and surface flaws.

Microscopic analysis revealed that both designs produced smooth surfaces at higher pressures (-85 kPa to -45 kPa). However, the Support design maintained acceptable finishes down to -25 kPa, while the Flat block exhibited roughness and edge chipping below -35 kPa. The optimized vacuum channel configuration of the Support design contributed to its superior performance.

These results highlight the importance of uniform suction forces and optimized designs for achieving precision machining outcomes. Future work could explore integrating dynamic pressure controls and real-time monitoring to enhance system performance and sustainability, offering practical solutions for industrial applications.

Acknowledgements

The financial support for this research was provided by Malaysia Ministry of Higher Education for the financial funding under Grant No. MTUNC/2019/FTKMP-COSSID/MC0012 throughout this project.

Author Contributions

All authors contributed toward data analysis, drafting, and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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