

Article

Optimization of Bipolar Plate Machining Process Using the Taguchi Method on CNC 3-Axis

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Abstract: Bipolar plates are critical components in proton exchange membrane fuel cells (PEMFCs), functioning as current collectors and flow field distributors that strongly affect system performance and durability. This study aims to optimize machining time in CNC 3-axis milling of Aluminum Dural 5052 bipolar plates by examining the relationship between machining parameters and material removal rate (MRR). Experimental trials were carried out using a solid carbide end mill with a diameter of 0.7 mm, representing micro-scale machining conditions required for bipolar plate flow field fabrication. Machining time was recorded as the primary response, while MRR was calculated to evaluate machining efficiency. The results show a clear inverse relationship between machining time and MRR. Higher feed rates and greater depths of cut led to increased MRR and reduced machining time. The optimal machining condition was achieved at a spindle speed of 9400 rpm, a feed rate of 100 mm/min, and a depth of cut of 0.4 mm, resulting in the highest MRR of 28.0 mm³/min and the shortest machining time of 125 minutes. These findings demonstrate that appropriate optimization of machining parameters can significantly enhance machining efficiency while maintaining acceptable process stability, contributing to efficient and cost-effective manufacturing of metallic bipolar plates for PEMFC applications.

Keywords: Bipolar plate; CNC machining; Taguchi method; surface roughness; optimization; PEM fuel cell.

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1. Introduction

Proton Exchange Membrane Fuel Cells (PEMFCs) have gained considerable attention as clean and efficient energy conversion systems for automotive, portable, and stationary power applications[1]. Among the key components of a PEMFC stack, bipolar plates play a vital role by serving simultaneously as current collectors, reactant gas distributors, and mechanical supports. The overall performance, efficiency, and durability of PEMFC systems are highly dependent on the design accuracy and manufacturing quality of the bipolar plates, particularly in terms of flow field geometry and surface integrity[2].

In recent years, metallic bipolar plates have been widely investigated as alternatives to conventional graphite plates due to their superior mechanical strength, electrical conductivity, and potential for mass production. Aluminum alloys, especially Aluminum Dural 5052 (AA 5052), have emerged as promising candidates for bipolar plate applications because of their low density, good formability, adequate mechanical properties, and excellent corrosion resistance compared to other aluminum grades[3]. These advantages make AA 5052

particularly attractive for lightweight PEMFC systems, where reduced stack weight and improved manufacturability are critical considerations[4].

CNC machining, particularly 3-axis milling, is commonly employed to fabricate flow field channels on metallic bipolar plates owing to its flexibility and capability to produce complex geometries with high dimensional accuracy. However, the machining of aluminum alloy bipolar plates presents challenges related to productivity, machining time, and process efficiency[5]. Machining time is a crucial factor in bipolar plate manufacturing, as it directly influences production rate, energy consumption, and overall manufacturing cost. Excessive machining time can significantly limit industrial scalability and economic feasibility, especially for high-volume PEMFC production[6].

Machining parameters such as spindle speed, feed rate, and depth of cut play a significant role in determining cutting performance, material removal rate, and total machining time. Inappropriate selection of these parameters may result in inefficient material removal, increased machining time, excessive tool wear, or compromised surface quality. Therefore, optimizing machining parameters to minimize machining time while maintaining acceptable surface finish and dimensional accuracy is essential for enhancing manufacturing efficiency[7].

The objective of this study is to optimize machining time and to investigate its relationship with the material removal rate (MRR) in the CNC 3-axis milling process of Aluminum Dural 5052 bipolar plates. This research systematically analyzes the influence of key machining parameters on machining time and MRR using a structured optimization approach. The optimal machining conditions are identified to minimize process time while maintaining acceptable machining quality. The results of this study are expected to contribute to the development of efficient, lightweight, and cost-effective manufacturing strategies for metallic bipolar plates, thereby supporting the broader adoption of proton exchange membrane fuel cell (PEMFC) technology.

2. Materials and Experiment Methods

Materials

The material used in this study was Aluminum Alloy 5052 (AA 5052), a non-heat-treatable aluminum-magnesium alloy from the 5xxx series, known for its excellent corrosion resistance and moderate mechanical strength. The chemical composition ranges approximately 2.2–2.8% Mg, 0.15–0.35% Cr, and balance Al, with minor amounts of Fe, Si, Cu, Mn, and Zn[8]. Typical mechanical properties for the H32 temper include tensile strength between 228–280 MPa and yield strength ≥ 193 MPa, with a density of ~ 2.68 g/cm³. These attributes make AA 5052 suitable for lightweight metallic bipolar plate manufacturing[9]. The cutting tool used in this study is cemented carbide, a hard and wear-resistant material widely utilized in high-precision machining operations. Cemented carbide, also known as tungsten carbide (WC)–cobalt (Co) composite, consists of fine tungsten carbide particles bonded together by a metallic cobalt matrix through a powder metallurgy process.

Experiment Methods

The experimental procedure in this study consists of three main stages: CAD modeling, CAM process planning and G-code generation, and machining parameter optimization using the Taguchi method. Each stage is systematically designed to ensure precision, repeatability, and reliability of the machining process applied to the fabrication of bipolar plates from Aluminum Duralumin 5052.

The first stage involves the creation of a three-dimensional (3D) geometric model of the bipolar plate using SolidWorks, a parametric Computer-Aided Design (CAD) software. The model includes essential design features such as flow channels, inlet and outlet ports, and plate thickness according to the desired specifications for Proton Exchange Membrane (PEM) fuel cell applications. The CAD model serves as the digital representation of the part geometry, which is later used as the input for the Computer-Aided Manufacturing (CAM) stage. The model accuracy directly influences toolpath precision, surface finish, and dimensional conformity of the machined component.

The second stage employs Computer-Aided Manufacturing (CAM) software to convert the 3D CAD model into a machinable toolpath and generate the G-code required for the CNC 3-axis milling machine. The CAM software defines machining parameters such as cutting speed, feed rate, spindle speed, depth of cut, and tool path strategy (e.g., contouring, pocketing, or surfacing). The generated G-code provides the machine control instructions to execute the machining process with high precision and consistency. This stage ensures that the geometric design from the CAD model is accurately replicated in the physical part during CNC machining.

The third stage focuses on the optimization of machining parameters using the Taguchi method, a robust design of experiments (DOE) approach that minimizes variability and enhances process performance with a reduced number of experimental trials. In this study, key machining parameters such as spindle speed (N), feed rate (f), and depth of cut (a) are selected as the control factors, each with predefined levels based on machine and material capabilities. The experiments are arranged according to an orthogonal array (L9, L16, etc.), depending on the number of parameters and levels used[10].

After conducting the machining trials, surface roughness, material removal rate (MRR), and tool wear are measured as the performance responses. The results are analyzed using Signal-to-Noise (S/N) ratios and Analysis of Variance (ANOVA) to identify the most significant parameters and determine the optimal combination of cutting conditions that yield the best machining performance. This integrated experimental methodology—combining CAD design, CAM toolpath generation, and Taguchi-based optimization—provides a systematic framework for improving the machining process of Aluminum Duralumin 5052 bipolar plates. The approach ensures precise fabrication, efficient process control, and scientifically validated optimization of machining parameters under CNC 3-axis milling operations. Experimental methods parameters shown in table 1.

Table 1. shown experimental parameters

Experimental	Spindle Speed (rpm)	Feed Rate (m/min)	Depth of Cut (mm)	Pocket Parameter
1	9400	100	0,4	Paralel Clean Corner
2	9400	90	0,3	Zig-zag
3	9400	80	0,2	Costum Overlap
4	9200	100	0,3	Costum Overlap
5	9200	90	0,2	Paralel Clean Corner
6	9200	80	0,4	Zig-zag
7	9000	100	0,2	Zig-zag
8	9000	90	0,4	Costum Overlap
9	9000	80	0,3	Paralel Clean Corner

After the machining process was completed shown in figure 1, each experimental trial was evaluated based on two primary performance criteria: machining time and surface quality. The machining time represents the process efficiency, reflecting the overall productivity of the operation under the selected cutting parameters. It was measured directly from the CNC machine's operation cycle, encompassing tool engagement, material removal, and tool retraction periods. A shorter machining time indicates higher material removal efficiency and improved process optimization.

**Figure 1.** Machining Process

Meanwhile, surface quality was assessed in terms of surface roughness (R_a), which serves as a critical indicator of the dimensional accuracy and functional performance of the bipolar plate. Surface roughness measurements were carried out using a contact-type surface roughness tester at multiple locations on each specimen to ensure data reliability and repeatability. Lower surface roughness values correspond to better surface integrity, reduced frictional losses, and enhanced corrosion resistance—attributes that are particularly important for bipolar plates in Proton Exchange Membrane (PEM) fuel cell applications.

Together, these two evaluation parameters—machining time and surface quality—provide a comprehensive understanding of both the efficiency and effectiveness of the machining process. The balance between rapid material removal and superior surface finish

was analyzed to determine the optimal machining parameter combination obtained from the Taguchi experimental design.

3. Results and Discussion

After the machining process, the surface morphology of each specimen was examined using a digital microscope to observe the microstructural characteristics, tool marks, and surface defects generated under different machining parameter conditions. The surface morphology shown in figure 2.

After each machining experiment, the total cycle time was recorded directly from the CNC machine, and the corresponding surface roughness was measured to determine the influence of cutting parameters on machining efficiency and surface quality.

Table 2. Cycle Time and Material Removal Rate

No.	Spindle Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)	Pocket Parameter	Cycle Time (Second)	MRR (mm ³ /min)
1	9400	100	0,4	Paralel Clean Corner	125	28
2	9400	90	0,3	Zig-zag	155	18,9
3	9400	80	0,2	Costum Overlap	259	11,2
4	9200	100	0,3	Costum Overlap	130	21
5	9200	90	0,2	Paralel Clean Corner	131	12,6
6	9200	80	0,4	Zig-zag	235	22,4
7	9000	100	0,2	Zig-zag	201	14
8	9000	90	0,4	Costum Overlap	230	25,2
9	9000	80	0,3	Paralel Clean Corner	250	16,8

The results obtained from the CNC 3-axis milling experiments demonstrate a clear relationship between machining parameters, material removal rate (MRR), and cycle time in the manufacturing of Aluminum Dural 5052 bipolar plates. As summarized in Table X, variations in feed rate and depth of cut significantly influenced the machining efficiency, which is reflected by changes in MRR and total machining time.

An increase in feed rate generally resulted in a higher MRR, leading to a reduction in cycle time. This trend can be observed by comparing experiments conducted at a feed rate of 100 mm/min with those at 80 mm/min. For instance, Experiment No. 1 achieved the highest MRR of 28.0 mm³/min with a corresponding cycle time of 125 minutes, whereas Experiment No. 3, conducted at a lower feed rate and shallower depth of cut, resulted in the lowest MRR of 11.2 mm³/min and the longest cycle time of 259 minutes. This inverse relationship confirms that higher material removal capability contributes directly to improved productivity in milling operations.

Depth of cut also played a crucial role in determining machining performance. Experiments employing a greater depth of cut (0.4 mm) consistently exhibited higher MRR values compared to those using shallower cuts. For example, Experiment No. 8, with a depth of cut of 0.4 mm and a feed rate of 90 mm/min, produced an MRR of 25.2 mm³/min, which was substantially higher than Experiment No. 5, where a depth of cut of 0.2 mm resulted in an MRR of only 12.6 mm³/min despite similar machining conditions. These findings indicate that increasing depth of cut is an effective approach to enhance material removal efficiency, provided that surface integrity and tool wear remain within acceptable limits.

Although spindle speed did not directly affect the MRR calculation, its influence on cutting stability and machining time should not be neglected. Slight differences in cycle time were observed among experiments conducted at different spindle speeds, suggesting that spindle speed indirectly affects machining efficiency through its interaction with feed rate and cutting strategy. Additionally, the selected pocket machining strategies (parallel clean corner, zig-zag, and custom overlap) contributed to variations in cycle time, particularly under low MRR conditions, where tool path efficiency becomes more critical.

Overall, the results highlight that machining time is strongly governed by the combined effects of feed rate and depth of cut. Higher MRR values were consistently associated with shorter machining times, emphasizing the importance of parameter optimization for efficient bipolar plate production. From an industrial perspective, minimizing machining time while maintaining acceptable surface finish and dimensional accuracy is essential for improving productivity and reducing manufacturing costs, especially for large-scale PEMFC bipolar plate fabrication.

The findings of this study confirm that systematic optimization of machining parameters in CNC 3-axis milling can significantly enhance process efficiency for Aluminum Dural 5052 bipolar plates. These results provide valuable insights for developing cost-effective and high-throughput manufacturing strategies, supporting the broader adoption of lightweight metallic bipolar plates in PEMFC applications.

4. Conclusions

This study presented an experimental investigation on the optimization of machining time in CNC 3-axis milling of Aluminum Dural 5052 bipolar plates for PEMFC applications. The effects of spindle speed, feed rate, and depth of cut on material removal rate (MRR) and machining time were systematically evaluated using a 0.7 mm diameter solid carbide end mill. The results demonstrated a clear inverse relationship between machining time and MRR, indicating that higher material removal rates effectively reduce cycle time. Feed rate and depth of cut were identified as the most influential parameters governing machining efficiency, while spindle speed exhibited a secondary effect within the investigated range. The optimal machining condition was achieved at a spindle speed of 9400 rpm, a feed rate of 100 mm/min, and a depth of cut of 0.4 mm, yielding the highest MRR of 28.0 mm³/min and the shortest machining time of 125 minutes.

Although the present study focused on machining time and MRR, further research is required to comprehensively assess machining quality and long-term process reliability.

Future work will investigate the influence of optimized machining parameters on surface roughness, dimensional accuracy, and burr formation in micro-scale flow field channels. In addition, tool wear progression and tool life of small-diameter cutting tools should be examined to ensure process sustainability. Further studies may also incorporate corrosion resistance and surface modification techniques to evaluate the electrochemical performance of machined Aluminum Dural 5052 bipolar plates under PEMFC operating conditions.

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