ENHANCING ROBOTIC TRIMMING ACCURACY OF CARBON FIBER REINFORCED POLYMERS: INVESTIGATING THE IMPACT OF CUTTING PARAMETERS

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ABSTRACT: *This study investigates the impact of cutting parameters on the accuracy of robotic trimming of Carbon Fibre Reinforced Polymers (CFRPs). The research focuses on analyzing cutting forces and their influence on part quality during the trimming process. Experiments were conducted using a six-axis industrial robot equipped with a high-speed spindle, with cutting forces measured in the x, y, and z directions. Results indicate that higher cutting speeds and feed lead to increased cutting forces, which in turn leads to elevated inaccuracies in the parts being machined. The study emphasizes the importance of understanding cutting force behavior for optimizing machining parameters and improving part quality. Findings suggest the need for advanced control strategies to mitigate dynamic errors and enhance machining accuracy in CFRP trimming applications.*

KEYWORDS: *Robotic trimming; Carbon fibre reinforced polymers; Cutting parameters; Cutting forces; Machining accuracy*

1 INTRODUCTION

The emergence and progressive development of advanced composite materials like Carbon Fiber Reinforced Polymers (CFRPs) in the past three decades have resulted in notable advancements in the manufacturing sector. This is attributed to their exceptional mechanical and physical characteristics, including high strength, stiffness, lightweight nature, durability, and exceptional resistance to corrosion. For a comprehensive exploration of the application of these advanced composite materials across various industries, refer to [1].

CFRP components are often manufactured to near-net shape, typically appearing rough and aesthetically unrefined. However, for certain applications, additional trimming and drilling processes are necessary to achieve the final shapes and dimensions of CFRP parts. Furthermore, CFRPs exhibit natural inhomogeneity and anisotropy within each layer. Consequently, their anisotropic and abrasive nature gives rise to various machining challenges, including rapid tool wear, matrix cracking, thermal damage, fiber pull-out, fiber fracture, and delamination [2]. Addressing these machining issues associated with CFRPs demands considerable attention from both the scientific community and industry to develop a thorough understanding of this crucial manufacturing process [3]. For further insights into machining composite materials, refer to [2–8].

Trimming is a commonly performed task in the fabrication process of CFRP parts. While CNC machine tools are traditionally used for CFRP trimming, they have limitations such as restricted working areas, reduced flexibility, high initial costs, and higher operating expenses. Robotic trimming presents a viable alternative to CNC trimming, offering adaptability, programmability, high dexterity, and maneuverability. Industrial robots provide advanced and cost-effective solutions compared to machine tools for achieving the final shapes and dimensions of molded CFRP parts. These robots have already demonstrated success in various industrial applications like welding, painting, and assembly. They are more cost-effective, flexible, and offer a larger working area compared to machine tools. However, during heavy cutting operations, robotic systems, due to their serial structure, are prone to errors stemming from various sources, including geometric inaccuracies, servo errors, and deflections of the end-effector caused by cutting forces and torques [8-14].

In recent years, numerous research studies have demonstrated the impressive capabilities of industrial robots across various machining tasks, including polishing [15], grinding [16–19], deburring [20-21] and end-milling [22]. However, there has been a relative scarcity of research focusing on robotic applications in the cutting process [11, 23-25]. It is widely acknowledged that heavy cutting operations tend to result in less accurate components compared to lighter cuts. Moreover, when robotic machining involves Carbon Fibre Reinforced Polymer (CFRP), the inherent anisotropic and highly abrasive nature of CFRPs, coupled with the lower stiffness of the robot and higher cutting forces, contribute to a multitude of machining challenges that impact the quality of machined parts.

The aim of this research is to investigate and analyze the various sources of error that influence the precision of machined components when employing high-speed robotic trimming techniques on CFRP materials. Through a comprehensive examination, this study seeks to identify and understand the factors contributing to inaccuracies in the robotic machining process.

2 EXPERIMENTAL PROCEDURE

Experiments were conducted utilizing a six-axis KUKA KR 500-2 MT industrial robot, which was installed on a 13-foot linear rail system and equipped with a robust spindle, specifically the HSD Mechatronic ES 789, capable of reaching spindle speeds of up to 26,000 rpm (as illustrated in Figure 1). The robot's operation was programmed using the CAD/CAM Robot-master software, boasting a substantial payload capacity of 500 kg.

The trimming process was executed in a downward direction parallel to the linear axis of the robot, as depicted in Figure 1. At each designated position, the distance from the base of the robot to the tool was precisely set at 2669 mm.

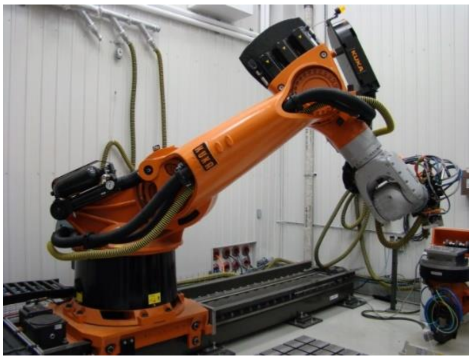

Fig. 1. Six-axis KUKAKR500-2MT industrial robot

The specimens utilized in the machining experiments were fabricated under stringent aeronautical conditions employing pre-impregnated technology. These laminates underwent autoclave curing, with careful ply orientation to achieve quasi-isotropic characteristics. Specifically, the 24-ply laminate measured 3.68 mm in thickness, boasting a fiber volume fraction of 64%. This meticulous preparation ensured uniform material properties conducive to accurate machining assessments.

Prior to commencing the initial trimming trial, the laminates underwent pre-drilling to enable secure fastening onto a machining fixture, as illustrated in Figure 2. This pre-drilling step was essential for affixing the laminate onto the fixture, facilitating smooth cutter entry into the material, and mitigating transient vibrations to achieve a consistent feed during slot machining under various cutting conditions. The aluminum back plating system depicted in Figure 2, comprising 49 screws and a torque wrench for laminate fixation, was specifically designed to accommodate the trimming of 36 slots across diverse cutting scenarios. The experimental design encompasses a comprehensive range of speeds, including values of 200, 300, 400, 500, 600, and 650 RPM, as well as a varied feed range spanning from 0.2540 to 0.5032 mm/rev. With each factor featuring six distinct levels, the design yields a total of 36 unique combinations. These permutations of cutting parameters were meticulously chosen to cover a broad spectrum of conditions, ensuring a thorough exploration of the trimming process during the experimental trials.

After the assembly process, the laminate-back plate unit was secured onto a Kistler 9255B dynamometer table to ensure stability in three axes. Subsequently, this setup was placed onto the KUKA DKP-400 two-axis positioning table, as shown in Figure 1, positioned within the operational range of the robot. Throughout the trimming experiments, both the positioning table and the robot's linear axis remained fixed.

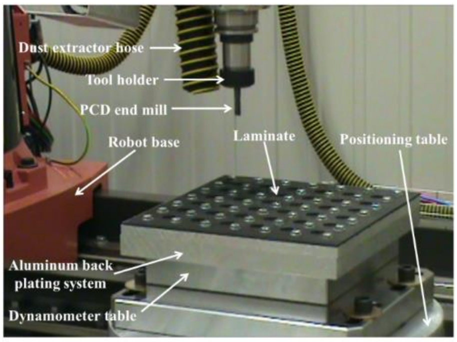

Fig. 2. Experimental Setup for Robotic Trimming of CFRP Components

A 9.525 mm diameter PCD end mill with two straight flutes, featuring a 20° rake angle, a 10° relief angle, and a 5 μm cutting edge radius, was employed for trimming the coupons. Prior to commencing the machining process, thorough inspection of the cutter was conducted.

Robotic trimming of CFRPs can generate significant dust, posing hazards to human health due to its harmful nature. Hence, it's imperative to have a dust extraction system in place. During the tests, CFRP robotic trimming was conducted within a confined space outfitted with cameras and a robust dust extraction setup to ensure safety and cleanliness.

3 RESULTS AND DISCUSSION

As depicted earlier, the initial rough part illustrated in Figure 2 underwent trimming to create 36 slots under various cutting conditions, as shown in Figure 3. Following the completion of the trimming process, the subassembly consisting of the trimmed laminate and back plate was transferred to a Mitutoyo CRYSTA coordinate measuring machine (CMM) for thorough inspection, as depicted in Figure 4. This inspection was essential to assess the dimensional accuracy and quality of the machined slots.

Fig. 3. State of the part after the trimming operation

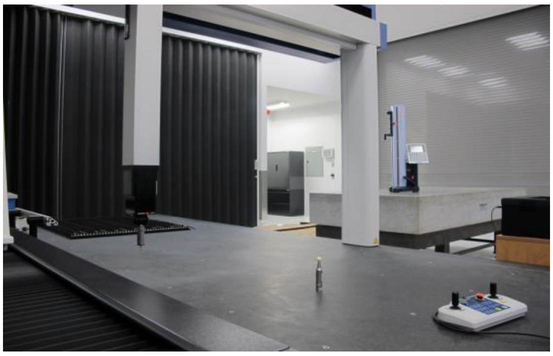

Fig. 4. Mitutoyo CRYSTA coordinate measuring machine (CMM)

Figures 5 and 6 illustrate the outcomes of the CMM inspection for selected specimens, considering various cutting velocity and feeds for up-cut milling. The specimens chosen for analysis are depicted in Figure 7. In Figure 5, a comparison is presented among the measured path errors at a cutting velocity of 200 m/min for different feeds, while Figure 6 showcases a comparison among the measured path errors at a feed of 0.2540 mm/rev and varying cutting velocity. These figures distinctly demonstrate the significant influence of both speed and feed on path deviation. Each cutting condition exhibits distinct wavy paths, indicating the pronounced impact of speed and feed on path accuracy. Particularly at high cutting conditions, dynamic errors emerge as a notable source of inaccuracies, adversely affecting path accuracy.

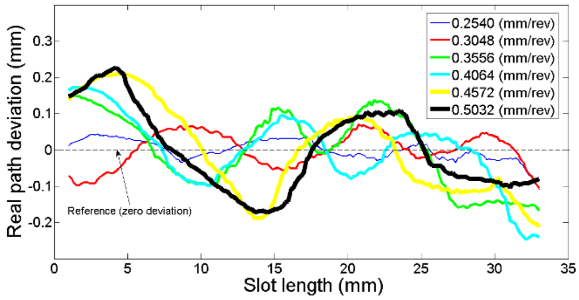

Fig.5. Measured Deviation of Trimmed Specimens at 200 m/min Cutting Velocity

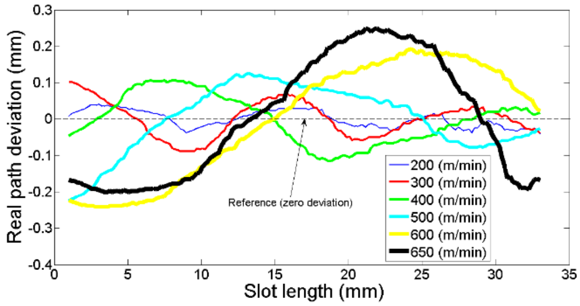

Fig.6. Measured Deviation of Trimmed Specimens at 0.2540 mm/rev Feed

The presence of high-amplitude vibrations along the measured path strongly influences the precision of the trimmed part. This phenomenon is attributed to fluctuations in cutting force during machining and the inherent flexibility in the joints, leading to vibrations in the end-effector.

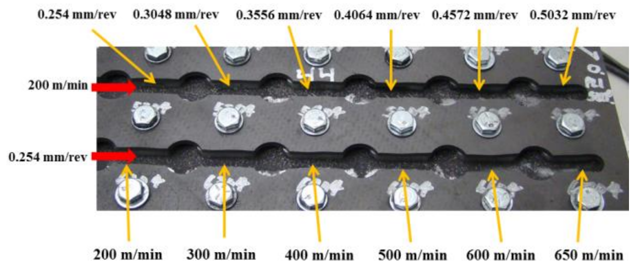

Figure 7: Selected Specimens for Analysis

Understanding cutting forces in robotic trimming processes is paramount, as they serve as crucial indicators of machining conditions. These forces often lead to deflections that can compromise part quality. To gain deeper insights into cutting force behavior, measurements were taken in the x, y, and z directions using a 3-axis dynamometer table, and the resulting data were meticulously recorded for further analysis.

Figures 8 and 9 depict the evolution of resultant cutting forces relative to both feed and cutting velocity. Notably, the data reveal a direct correlation between increasing feed or cutting velocity and rising cutting forces. This trend arises because higher feeds and cutting velocity result in greater resistance from the laminate, necessitating increased force to maintain cutting efficiency. Consequently, as cutting forces escalate, so do robot deflections and path deviations, underscoring the need for effective force management strategies to ensure optimal trimming outcomes.

It's crucial to acknowledge that an industrial robot's dynamic performance is inherently less uniform than its static counterpart. Specifically, minimizing displacements in the main joints, particularly joint 1, contributes to improved dynamic performance.

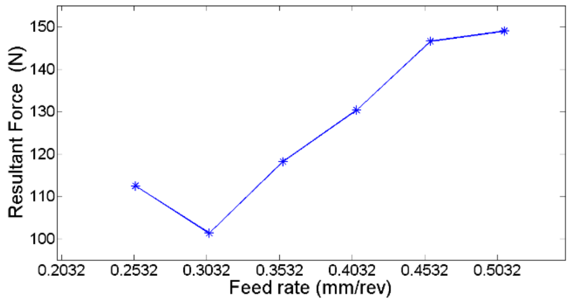

Fig.8. Resultant Cutting Force Variation with Feed at 200 m/min Cutting Velocity

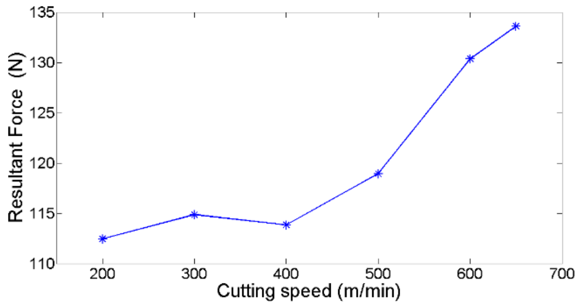

Fig.9. Resultant Cutting Force Variation with Cutting velocity at 0.2540 mm/rev Feed

Figure 10 provides a comprehensive 3D plot showcasing profile deviation as a function of cutting velocity and feed across all cutting conditions tested. The results reveal that profile deviations range from 0.28 mm to 1.08 mm, with deviations generally increasing as feed and cutting velocity rise. Optimal cutting conditions are observed at low feeds (0.2540 mm/rev) and low cutting velocity (200 m/min), highlighting the importance of carefully selecting operating parameters to achieve desired machining precision.

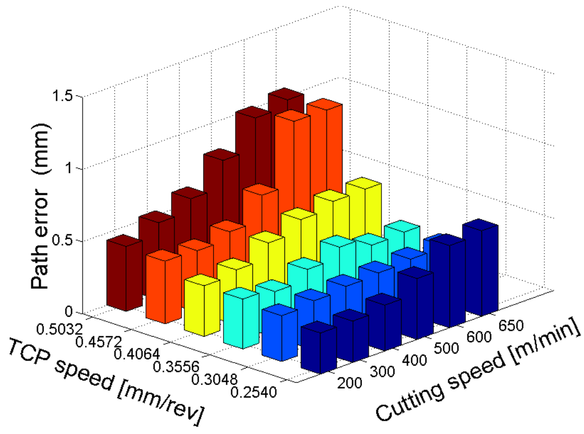

Fig. 10. Path Error Variation with Cutting Speed and Feed Rate for All Tested Cutting Conditions

4 CONCLUSION

The study presented a comprehensive analysis of robotic trimming of Carbon Fibre Reinforced Polymers (CFRPs), focusing on the effects of cutting parameters on machining accuracy and quality. Through experimental trials and measurements, various factors influencing the trimming process were investigated, including cutting speed, feed rate, cutting forces, and path deviation.

The results revealed significant insights into the behavior of CFRPs during robotic trimming. It was observed that higher cutting speeds and feed rates led to increased cutting forces, resulting in elevated inaccuracy of the machined part. Additionally, the study highlighted the importance of understanding and controlling cutting forces, as they are critical indicators of machining conditions and directly impact the quality of machined parts.

Furthermore, the experiments demonstrated the potential of industrial robots for CFRP trimming, showcasing their adaptability and cost-effectiveness compared to traditional machining tools. However, it was noted that robot deflection and dynamic performance could pose challenges, particularly under high cutting forces.

Future research could focus on advanced control strategies to mitigate robot deflection and dynamic errors, ultimately enhancing the efficiency and reliability of robotic trimming operations in aerospace and other industries.

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