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Optimized fixture design for precision machining of tensile specimens in hybrid composites

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Abstract

Although CNC machines offer numerous advantages, machining hybrid composites presents unique challenges, particularly in the proper positioning and securing of tensile specimens during the process. These materials, often comprising layers of different types, can behave unpredictably under cutting forces, complicating the task of achieving precise, standard-compliant shapes. This study introduces a specialized machining fixture developed to securely hold and manipulate tensile specimens for composite testing, meeting the stringent requirements of academic research where dimensional precision is paramount. The fixture's design features robust clamping mechanisms that stabilize various specimen geometries, ensuring minimal distortion and precise alignment during CNC machining. The fabrication process included careful material selection and the application of advanced machining techniques to achieve exceptional dimensional accuracy. Performance evaluation through machining trials assessed factors such as clamping force, stability, and usability. Results demonstrate that the proposed fixture significantly enhances machining efficiency and accuracy, thereby improving the reliability of composite material testing.

Keywords: CNC precision machining; tensile specimen preparation; hybrid composite materials; International standards (ISO, ASTM).

1. Introduction

The machining of hybrid composites represents a rapidly growing field in modern industrial sectors due to their advantageous properties, such as lightness, mechanical strength, and durability [1–3]. However, these materials also pose unique manufacturing challenges, particularly regarding the precision and surface quality required to meet stringent standards such as those defined by ISO and ASTM [4–7]. Therefore, the programming and machining of these materials demand advanced technologies and methodical approaches. Although CNC machines offer benefits, machining hybrid composites presents particular difficulties, especially concerning the positioning and holding of specimens during machining. These materials, typically composed of different layers, can exhibit unexpected behaviors when subjected to cutting forces, making it challenging to achieve precise shapes that conform to standards. To overcome these difficulties, it is imperative to design an appropriate machining fixture. This fixture must ensure the stability and precision of the specimen holding throughout the machining process. Thus, this study proposes to create and test a specific fixture, examining its impact on the quality of the machined samples. The second aspect of this article is the programming and machining of hybrid composite tensile specimens using a CNC machine equipped with the Siemens Sinumerik 828 D G-code guide [8]. The choice of this system is based on its advanced control and

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precision capabilities, which are crucial for achieving results that meet normative requirements. The study revolves around several essential steps: the design of the machining fixture, the definition of cutting parameters, the creation of specific G-code programs, and the machining of the fixtures and tensile specimens. The first step of this study involves the design of the machining fixture (figure 01), carried out using SolidWorks software. The design was developed based on the dimensions of a standard ASTM tensile specimen.

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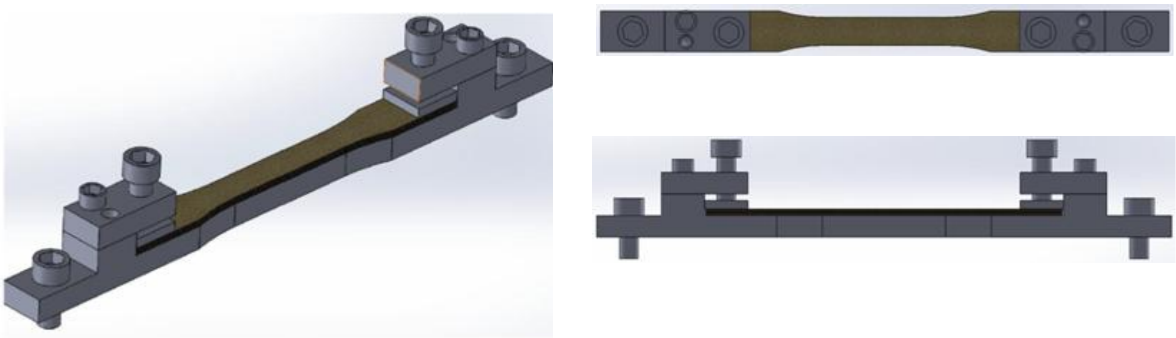

Fig. 1. Developed machining setup

The dimensions of the fixture were chosen to allow the simultaneous machining of three to four specimens, depending on their thicknesses and the dimensions of the CNC machine table. The material selected for the machining fixture is aluminum, given that the cutting forces required for machining composites are lower compared to those for metals [9]. This design ensures stable fixation and secure holding of the specimens during machining, while optimizing process efficiency by allowing the production of multiple specimens in a single operation.

The definition of cutting parameters is fundamental to ensuring the efficiency and quality of the machining process. Cutting parameters must be carefully selected to adapt to the properties of hybrid composites, which can vary significantly depending on the materials used and their composition. In this study, emphasis was placed on optimizing these parameters to minimize tool wear and maximize the surface quality of the machined parts [10–13]. The creation of G-code programs constitutes the second critical step of the process. The Siemens Sinumerik 828D G-code guide (Figure 2) was chosen for its ability to handle complex machining processes with high precision. G-code, the programming language used to control CNC machines, must be developed with care to ensure that cutting paths and machining strategies comply with the design specifications of the tensile parts. Using this guide allows for standardizing and optimizing programming, thereby reducing the risk of errors and improving the reproducibility of results [8, 14].

Fig. 2. HMI SINUMERIK 828d

The actual machining of the fixtures and tensile specimens constitutes the final phase of the study. The fixtures, made of aluminum, play a crucial role in holding the tensile parts in position and ensuring their stability during machining. Aluminum was chosen for its favorable mechanical properties and ease of machining, allowing for the creation of precise and robust fixtures. The optimization of cutting strategies for hybrid composites resulted in tensile specimens that meet ISO and ASTM standards in terms of dimensions and surface quality [15–17].

The main interest of this study lies in validating the effectiveness of the Siemens Sinumerik 828D G-code guide for machining hybrid composites. The results show that this approach allows for the production of high-quality parts that meet the stringent requirements of international standards. This validation opens promising prospects for the application of this technology in various industrial sectors, where the precision and surface quality of machined parts are essential. Programming and machining hybrid composite tensile parts using the Siemens Sinumerik 828D G-code guide proves to be an effective and reliable approach to meet modern industrial requirements. This study demonstrates that, through the precise definition of cutting parameters, rigorous creation of G-code programs, and optimization of cutting strategies, it is possible to produce tensile specimens that comply with ISO and ASTM standards. These results validate not only the effectiveness of the Siemens Sinumerik 828D G-code guide but also its potential for increased use in various industrial applications.

2. Materials and Methods

The tensile specimens studied in this work are designed to meet standardized tensile testing standards, such as those defined by ASTM D3039 or ISO 527 (Figure 3). They are made of hybrid composites combining various natural fibers and transparent resin binders. The specific combinations used include (Figure 4).

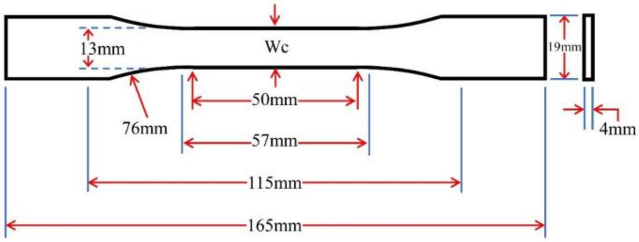

Fig. 3. The dimensions of the test piece

Fig. 4. The different materials of hybrid composite

2.1. Jute-Luffa

Natural fiber composites, such as jute and luffa composites, offer a balanced combination of strength and weight, making them ideal for various applications. Jute, known for its strength and durability, when combined with luffa, which offers lightweight and flexible properties, results in a composite material with excellent tensile strength and shock absorption capabilities. Studies have shown that jute and polyester composites with varying fiber lengths and weight percentages exhibit high flexural strength and modulus, indicating good fiber-matrix adhesion. Moreover, the use of natural fibers like jute and luffa in composite materials contributes to their low density, cost-effectiveness, and biodegradability, making them eco-friendly alternatives to traditional materials [18–21].

2.2. Alfa-Jute

Alfa fibers, derived from the Stipa tenacissima plant, exhibit remarkable rigidity and wear resistance. When combined with jute fibers, a hybrid composite is formed that leverages the mechanical strengths of both fibers. Alfa fibers have been extensively studied in various composites, showing significant improvements in mechanical properties when incorporated into cementitious matrices. Moreover, Alfa fibers have been used in unsaturated polyester resin composites, demonstrating enhanced tensile strength and Young's modulus with increasing fiber weight fractions. Additionally, treatments such as alkaline and hydrothermal treatments have been found to improve the flexural strength of Alfa fibers in cement mortars, thereby enhancing their long-term performance and matrix adhesion. The use of Alfa fibers in composite materials presents a promising pathway for applications requiring high mechanical strength and dimensional stability, making Alfa-jute composites a suitable choice for such demanding scenarios [22–26].

2.3. Alfa-Luffa

The combination of Alfa and luffa fibers in composites leverages the rigidity properties of Alfa fibers and the lightness of luffa, creating robust yet lightweight materials ideal for weight-sensitive applications.

Research indicates that Alfa fibers, when incorporated into composites, enhance tensile and flexural strength, while treatments such as alkaline and hydrothermal treatments improve the mechanical properties and adhesion of cement-based composites. Moreover, the use of raw Alfa fibers without intensive chemical treatment maintains the mechanical strength properties of the mortar, exhibiting good flexural and compressive strength even at low fiber concentrations. These findings highlight the potential of Alfa-luffa composites for lightweight structural components requiring both strength and vibration absorption capabilities, offering a promising solution for various applications needing lightweight yet robust materials [19], [27–30].

Epoxy and polyester resins are essential components of composite materials due to their mechanical properties and adhesive capabilities. Epoxy resins, when reinforced with materials like quartz fibers, exhibit improved thermal and mechanical properties, making them ideal for applications requiring durability and strength, such as protective housings for high-speed communication antenna systems. On the other hand, polyester binders, when modified with methylene diphenyl disocyanate, show enhanced adhesion and cohesion parameters, leading to improved tensile adhesive strength and flexural rupture stress, crucial for structural integrity and performance of composite materials. The choice of resin binder is crucial as it not only holds the fibers together but also facilitates load transfer between them, impacting the overall performance and reliability of the composite material in various applications [31–34].

2.4. Importance of standardized tensile specimens for mechanical testing

Mechanical testing is essential for characterizing hybrid composite materials and ensuring their performance and reliability in various industrial applications. Standardized tensile test specimens play a key role in these tests as they enable precise and reproducible evaluation of mechanical properties such as tensile strength (Figure 5), modulus of elasticity, and elongation at break. Research has shown that hybrid composites, combining natural fibers such as bamboo, sugarcane bagasse, and coconut fiber with matrices like epoxy, exhibit improved tensile and impact strengths, making them suitable for applications such as automotive body manufacturing. Furthermore, studies on polymer matrix composites, particularly polyamides PA 66 and PA 66-GF 30, highlight superior mechanical properties such as strength, toughness, and wear resistance, underscoring their relevance in sectors such as automotive engineering. Additionally, analysis of hybrid composites made from fabrics such as Vectran, Kevlar, and aluminum fiber demonstrates complex viscoelastic and mechanical responses, crucial for understanding their bi-elastic performances and failure mechanisms [35–37].

Fig. 5. Tensile test of a composite specimen

2.5 Standardization and reproducibility of tests

Standardized protocols established by organizations such as ASTM and ISO play a crucial role in ensuring comparability and accuracy of tensile testing results for composite materials. Research has shown that adhering to standardized dimensions and preparation methods, such as ASTM standards D638 and D3039-D3039M, can significantly reduce measurement errors and improve the reliability of mechanical testing results. Furthermore, advances in testing systems, such as the development of cost-effective 3D-printed tensile testers, provide customized solutions for characterizing materials at microscopic dimensions, bridging the technological gap for intermediate-scale samples.

While downsizing testing methods may present challenges, such as uncertainty in measuring the cross-sectional area of small samples, innovative approaches such as using full-field displacement data from digital image correlation in conjunction with finite element models have shown promising results in accurately calibrating constitutive models, especially for complex material behaviors like polymers. Additionally, proposed techniques for testing samples of varying thicknesses, as demonstrated in studies on raw sheets, provide a method to assess mechanical and plastic properties across different cross-sections, which is crucial for materials like hybrid composites with variable fiber distributions and matrix qualities [38-41].

2.6. Challenges in machining specimens

Machining hybrid composites for the production of standardized tensile specimens presents several technical challenges. These challenges are mainly related to positioning and securing the specimens during machining. The structural complexity of hybrid composites, which combine materials with varied properties, exacerbates these difficulties.

3. Positioning And Securing Challenges for Hybrid Composite Specimens

3.1. Structural complexity

Hybrid composites consist of layers of different materials, and this multi-layered structure can lead to unpredictable behaviors under cutting forces. For instance, differences in hardness and thermal resistance between the layers can cause delamination or surface defects during machining [42, 43].

3.2. Cutting forces

During machining processes, cutting forces can cause vibrations and unexpected movements in the workpiece, impacting dimensional accuracy and surface quality, especially in hybrid composites with complex internal structures. Studies on machining polymer composites demonstrate that tool selection and process parameters significantly influence feed forces and deformation, highlighting the need for careful optimization to minimize vibrations and ensure precise machining of hybrid composites. Hybrid composites are particularly sensitive to these disturbances due to the variability in their internal structure [44–47].

3.2. Fixing the specimens

Proper fixation of specimens to CNC machines is crucial to prevent movement during machining, especially for fragile hybrid composites sensitive to clamping pressures. Traditional fixation methods may not be suitable for these materials, as improper clamping can damage reinforcement fibers or the matrix, compromising sample integrity. To address this issue, innovative approaches such as specialized fixture design or using low clamping forces are recommended to avoid adverse effects on the composite structure during machining processes. It is essential to ensure secure yet gentle fixation methods to maintain structural integrity of the samples and achieve precise machining results without material damage. Additionally, regular monitoring and adjustment of fixation techniques based on specific characteristics of hybrid composites can help optimize machining outcomes while preserving material properties [48–50].

4. Development and Evaluation of a Suitable Machining Setup

4.1. Design of a Specific Assembly

To overcome the challenges of positioning and securing hybrid composite specimens during machining, a specific machining fixture will be designed. This fixture must ensure stable and secure fixation of the specimens, minimizing vibrations and unwanted movements. The design will take into account the peculiarities of hybrid composites, such as their fragility and sensitivity to clamping pressures (Figure 6).

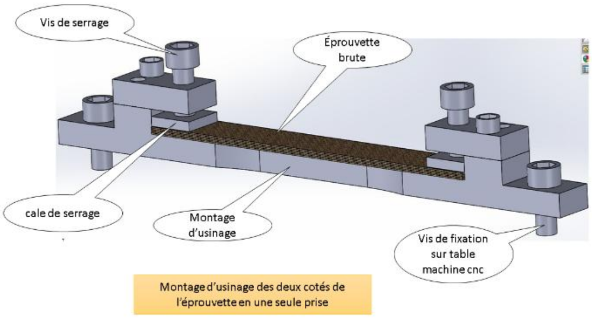

Fig. 6. Machining assembly assembly A effacer

4.2. Materials and Manufacturing Techniques

The selection of materials for the fixture and the manufacturing techniques employed will be crucial to ensure its robustness and adaptability. Soft yet effective clamping materials will be chosen to prevent damage to the specimens. The fabrication of the fixture will utilize precise methods, such as CNC machining, to ensure tight tolerances and high construction quality (Figure 7 and 8).

Fig. 7. Execution of assembly machining

Fig. 8. Raw specimen on the actual machining setup

4.3. Evaluation of Assembly Effectiveness

The developed fixture will be evaluated through a series of machining tests. Evaluation criteria will include fixture stability, dimensional accuracy of machined specimens, and surface quality. Test results will validate the fixture's effectiveness and guide necessary adjustments to optimize its performance.

4.4. Impact on Specimen Quality

The ultimate goal is to demonstrate that the developed machining fixture, combined with optimized CNC programming, can machine hybrid composite tensile specimens that meet standardized norms in terms of dimensions, tolerances, and surface quality. The study aims to prove that these innovations enhance the reliability of mechanical tests and characterization of hybrid composites.

5. Creation of the G-Code Program

The specific G-code program was created using the Siemens Sinumerik 828D guide (Figure 9). This guide offers advanced conversational programming capabilities, enabling the machining of outer contours on both sides of the specimens. With built-in trajectory creation functions, programming was simplified, ensuring optimal precision and increased efficiency in the machining process. The cutting trajectories (Figure 10) were defined to meet the design specifications of the tensile specimens, ensuring compliance with ISO and ASTM standards.

Fig. 9. Programming with the G-code

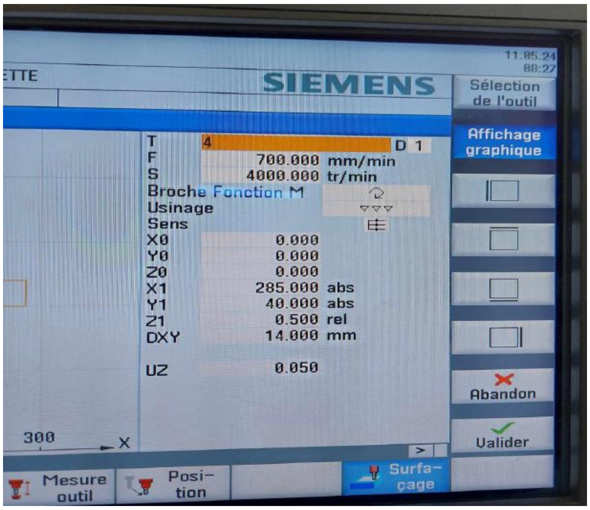

Fig. 10. Creation of the specimen outline

5.1 Simulation and validation

The program simulation is conducted to verify cutting trajectories and prevent collisions or errors. This simulation is essential to ensure machining safety and efficiency (Figure 11).

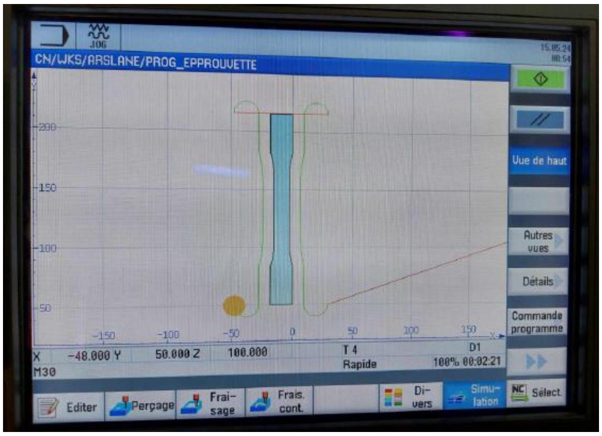

Fig. 11. Simulation of specimen machining

5.2 Execution of machining

After validation, the program is loaded into the CNC machine, and machining of the specimens is executed (Figure 12). Real-time monitoring is conducted to adjust parameters if necessary.

Fig. 12. Execution of the specimen machining program

5.3 Validation by Practical Tests

The optimized CNC programs will be validated through practical tests. Machined specimens will be measured and inspected to verify their compliance with standards. The results obtained will confirm the effectiveness of the chosen cutting parameters and allow for adjustments in programming if necessary to achieve the best possible results.

6. Discussion

This study explored the impact of designing a specific clamping device and using optimised G-code programming in the machining process of hybrid composites. The results obtained show that the optimisation of cutting parameters and the development of a tailored clamping system have a significant effect on dimensional accuracy, surface quality, and the stability of samples during machining.

6.1. Comparison with previous studies

Previous work on hybrid composite machining has shown that managing cutting forces and controlling vibrations are critical to ensuring optimal surface quality and avoiding delamination of composite layers [42, 43]. The use of a specific clamping device in this study, combined with optimised G-code programming, helped to minimise these adverse effects. Compared to more traditional clamping systems, this approach demonstrated more stable results, with better dimensional accuracy and fewer surface defects, highlighting the importance of innovation in the field of hybrid composite machining.

6.2. Influence of cutting parameters

The optimisation of cutting parameters—particularly spindle speed, depth of cut, and feed rate—played a crucial role in reducing tool wear and improving the surface finish of the machined parts. The findings of this study are consistent with previous research [10–13], which emphasised the importance of these parameters in achieving optimal performance during the machining of natural fibre composites. By carefully adjusting these parameters, it was possible to maintain process stability, enhance precision, and avoid deformations or damage to the composite materials, which are often more fragile than metallic materials.

6.3. Challenges in hybrid composite machining

Machining hybrid composites continues to present major challenges, mainly due to the variability of internal material structures and differences in stiffness and thermal resistance between layers. As reported in earlier studies, this heterogeneity can cause problems such as delamination or surface defects [44–47]. However, by using soft clamping materials and advanced programming techniques, this study significantly reduced such issues. The innovations proposed in this research offer a promising response to these challenges, providing practical solutions for industries where precision and surface quality are essential, such as aerospace and automotive sectors.

6.4. Industrial application perspectives

The results of this study pave the way for broader use of hybrid composites in various industrial applications. The effectiveness of the clamping system and G-code programming in machining hybrid composite samples could have important implications for industries that require lightweight and durable materials, such as automotive, aerospace, and construction. Moreover, the advancements made in the development of suitable clamping devices could potentially be extended to other types of composite materials, offering a flexible and reproducible solution for machining various complex materials.

6.5. Limitations and areas for improvement

Although this study demonstrated the benefits of designing a dedicated clamping system and optimising cutting parameters, certain limitations remain. For instance, implementing these techniques on a larger scale, particularly in mass production, would require further adjustments—especially regarding cost and large-scale reproducibility. Additionally, tool wear resistance during hybrid composite machining could be improved by using more advanced cutting materials or by further optimising cooling strategies. These areas represent opportunities for improvement and directions for future research.

7. Conclusion

This study emphasizes the critical role of designing specialized machining fixtures for producing hybrid composite tensile specimens. The fixture, designed with SolidWorks and based on ASTM specimen dimensions, enables the simultaneous machining of multiple specimens, thereby optimizing production efficiency. The selection of aluminum for the fixture, driven by the reduced cutting forces required for composites, ensured both stability and efficiency during machining.

Additionally, the study showcases the effectiveness of the Siemens Sinumerik 828D G-code guide in programming and machining processes. By focusing on key stages such as cutting parameter optimization, G-code creation, and the machining of both fixtures and specimens, this research demonstrates how advanced techniques and precision tools can consistently meet the stringent ISO and ASTM standards for dimensional accuracy and surface quality.

The results of this study, which adhere to international standards for dimensions and surface quality, not only validate the effectiveness of the Siemens Sinumerik 828D G-code guide but also highlight its potential for broader industrial applications. Despite the inherent challenges in machining hybrid composites, the study shows that high levels of precision and surface quality can be achieved through advanced CNC technologies and systematic approaches.

In conclusion, programming and machining hybrid composite tensile specimens using the Siemens Sinumerik 828D G-code guide proves to be a highly effective and reliable method. This work lays a strong foundation for ongoing improvements in manufacturing processes and the integration of advanced composite materials in various industrial sectors. The findings suggest that these technologies hold significant potential for enhancing innovation and efficiency in industrial production, making them a valuable tool for future advancements in the field.

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