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**INVESTIGATION OF MACHINABILITY IN THE MILLING PROCESS OF
CARBON FIBER-REINFORCED THERMOPLASTIC AND THERMOSET MATRIX
COMPOSITES**

Guaratinguetá

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**INVESTIGAÇÃO DA USINABILIDADE NO PROCESSO DE FRESAMENTO DE
COMPÓSITOS DE MATRIZ TERMOPLÁSTICA E TERMORRÍGIDA
REFORÇADOS COM FIBRA DE CARBONO**

Tese apresentada à Universidade Estadual Paulista (UNESP), Faculdade de Engenharia e Ciências, Guaratinguetá, para obtenção do título de Doutora em Engenharia.

Área de Concentração: Desenvolvimento e processamento de Materiais

Orientador: Prof. Dr. Manoel Cleber de Sampaio Alves

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IMPACTO POTENCIAL DESTA PESQUISA

O impacto potencial deste trabalho consiste na geração de conhecimento científico e tecnológico sobre a usinabilidade de compósitos de matriz termoplástica e termorrígida reforçados com fibra de carbono, contribuindo para o avanço do estado da arte em um tema ainda emergente. Sob a perspectiva técnico-científica, os resultados permitem a definição de parâmetros de fresamento e metodologias robustas capazes de assegurar integridade mecânica, qualidade superficial e viabilidade industrial de laminados estruturais espessos, viabilizando a substituição de estruturas metálicas por compósitos leves e de alto desempenho. Esses avanços tendem a impactar positivamente a competitividade da indústria nacional de manufatura avançada, com redução de custos, perdas de material e emissões e eficiência energética. A cooperação internacional estabelecida no desenvolvimento da pesquisa contribui para a internacionalização e a visibilidade científica do país. Adicionalmente, a aplicabilidade direta dos resultados em cadeias produtivas estratégicas, em âmbito nacional, aliada ao enfoque em materiais leves e processos otimizados, está alinhada aos princípios do desenvolvimento sustentável, consolidando a relevância científica, tecnológica e socioeconômica da tese.

POTENTIAL IMPACT OF THIS RESEARCH

The potential impact of this work lies in the generation of scientific and technological knowledge on the machinability of thermoplastic and thermoset-matrix composites reinforced with carbon fibers, contributing to the advancement of the state of the art in an emerging research field. From a technical–scientific perspective, the results enable the definition of milling parameters and robust methodologies capable of ensuring mechanical integrity, surface quality, and industrial feasibility of thick structural laminates, thereby enabling the replacement of metallic structures with lightweight, high-performance composites. These advances are expected to positively enhance the competitiveness of the national manufacturing industries through reductions in costs, material losses, and emissions, as well as improvements in energy efficiency. The international cooperation established during the development of the research contributes to the internationalization and scientific visibility of the country. In addition, the direct applicability of the results to strategic production chains at national level, combined with the focus on lightweight materials and optimized processes, is aligned with the principles of sustainable development, consolidating the scientific, technological, and socioeconomic relevance of this thesis.

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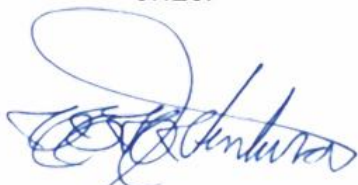
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This work is dedicated to my family.

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“Science knows no country, because knowledge belongs to humanity, and is the torch which illuminates the world.”

Louis Pasteur

ABSTRACT

Carbon fiber-reinforced polymers (CFRPs) are widely employed in automotive and aerospace applications due to their high strength-to-weight ratio. Although typically produced near net shape, machining is required to meet final dimensional accuracy and surface quality demands. However, their anisotropic, heterogeneous structure and the abrasiveness of carbon fibers often lead to critical surface and subsurface damage, making the machining of composites a challenge. This work investigates the machining by the milling of thermoplastic matrix composite (Toray Cetex[®] TC910PA6) and the thermoset matrix composite (Toray E732[®]) using four cutting tool geometries: two helical (i.e. the diamond-coated Neutral Helix (NH) and Left-hand helix (LH)) and two multi-edge (i.e. with Zr coating (ME-ZR) and with diamond coating DURA[®] (ME-D)). Milling tests were conducted varying the feed per tooth " f_z " (0.025; 0.050; 0.075 and 0.10 mm/t) and rotation " n " (4000 and 8000 rpm). Machinability was assessed through surface quality analysis, delamination occurrence and monitoring of cutting parameters influence on the power consumption, vibration of the system, acoustic emission and the wear of cutting tools. Statistical analyses of variance (ANOVA), analysis of means (ANOM), Signal-to-Noise analysis (S/N) and comparative and normality tests, as well optimization with the Response Surface Methodology (RSM) were applied evaluate parameter effects. Furthermore, static tests (i.e., tensile and static bending) and dynamic tests (i.e. axial fatigue) examined the influence of machining on mechanical performance. The thermoset composite presented increased resistance to cutting, with direct impact of the feed per tooth factor f_z that led to elevated incidence of discontinuous fiber rupture during machining that favored delamination type II when using higher feed per tooth values (0.075 and 0.10 mm/t). Additionally, several regions of porosity were observed and discontinuous distribution of fibers that led to increased roughness of 2.2 μm . The results revealed that reducing the feed can act as a mitigating factor to fiber pullout phenomena, providing a reduction in delamination. The thermoplastic composite presented fewer transient vibrational peaks, as well as lower power consumption during machining. The most influential parameter for the milling process was the f_z , resulting in surface finish improvement achieved with the application of 0.025 mm/tooth. Enhanced surface quality and reduction of lateral delamination was observed with the application of the Left-Hand helix tool (LH), with resulting R_a of 1.3 μm . The amplitude of power consumption was critically dependent on the change of cutting tool geometry, the multi-edge (ME-D) tool led to power consumption amplitudes that reached 4 times the average value of the helical cutting tools. The chips generated during machining presented drastically form change with the composite matrix variation due to different chip mechanism formation. Cutting tool geometry also affected chip formation in CFRP machining, the LH tool promoted best chip flow and superior surface finish, making them ideal for finishing machining. It was proven that the milling machining process did not reduce the static mechanical properties. However, significant impact in dynamic properties was confirmed to the condition $f_z = 0.02$ mm/t and $n = 4000$ rpm, where the machining resulted in delamination, reducing fatigue life for high stress levels (75 to 85%).

Keywords: Machining; Milling of CFRP; Statistical Analysis; Mechanical Properties.

RESUMO

Polímeros reforçados com fibras de carbono (CFRPs) são amplamente aplicados na indústria automotiva e aeronáutica devido a combinação de propriedades de resistência mecânica com a redução de peso de componentes. Embora geralmente produzidos em formato próximo ao final, componentes compósitos precisam ser usinados para atender aos requisitos de precisão dimensional e qualidade superficial. No entanto, devido à sua estrutura anisotrópica e heterogênea e a natureza altamente abrasiva das fibras de carbono, diversos danos críticos são observados durante o corte, o que torna a usinagem de compósitos um desafio. Este trabalho investiga a usinagem por fresamento do compósito de matriz termoplástica (Toray Cetex[®] TC910PA6) e do compósito de matriz termorrígida (Toray E732[®]) utilizando quatro geometrias de ferramentas de corte: duas helicoidais (Hélice neutra com revestimento diamantado (NH) e hélice à esquerda (LH)) e duas geometrias multi-arestas tipo sabugo (com polimento Zr (ME-ZR) e com revestimento diamantado DURA[®] (ME-D)). Ensaios de fresamento foram realizados variando o avanço por dente " f_z " (0,025; 0,050; 0,075 e 0,10 mm/dente) e rotação " n " (4000 e 8000 rpm). A usinabilidade foi avaliada por meio da análise da qualidade superficial, ocorrência de delaminação e danos e monitoramento da influência dos parâmetros de corte na potência consumida, vibração do sistema, emissão acústica e desgaste das ferramentas de corte. Foram aplicadas análises estatísticas de variância (ANOVA), médias (ANOM), sinal-ruído (S/N), testes comparativos e de normalidade, além de otimização utilizando a Metodologia de Superfície de Resposta (RSM). A influência da usinagem nas propriedades mecânicas foi investigada por meio de testes estáticos (tração e flexão) e dinâmicos (fadiga axial). Foi observada maior resistência ao corte para o compósito termorrígido, com grande dependência do fator avanço por dente f_z , que levou a maior incidência de ruptura descontínua das fibras favorecendo delaminação tipo II quando aplicados altos f_z (0,075 e 0,10 mm/dente). Regiões de porosidade e distribuição descontínua de fibras foram observadas para o compósito termorrígido que podem ter contribuído para alta R_a (2,2 μm). Foi constatado que a redução do avanço por dente pode atuar como fator atenuante no processo de arrancamento das fibras, proporcionando redução na delaminação. O compósito termoplástico apresentou menor incidência de picos vibracionais e menor amplitude de potência consumida, sendo avanço o parâmetro mais influente. Melhoria na qualidade superficial e redução em danos foi observada com a aplicação da ferramenta de hélice à esquerda (LH) associada a f_z de 0,025 mm/dente, com R_a de 1,3 μm . O consumo de potência foi criticamente dependente da mudança da geometria da ferramenta de corte. A ferramenta multi-arestas (ME-D) gerou amplitude 4 vezes maiores de potência que as ferramentas helicoidais. Os cavacos coletados apresentaram mudança drástica de forma e tipo com a variação da matriz, tendo a ferramenta (LH) promovido melhor fluxo de escoamento de cavacos, caracterizando como opção ideal para usinagem de acabamento. Foi comprovado que o processo de usinagem de fresamento não reduziu as propriedades mecânicas estáticas dos compósitos, porém, foi observado impacto significativo nas propriedades dinâmicas para a condição $f_z=0,02$ mm/dente e $n=4000$ rpm, onde a usinagem resultou em delaminação, reduzindo a vida em fadiga para altos níveis de tensão (75 a 85%).

Palavras-chave: Usinagem; Fresamento de CFRP; Análise Estatística; Propriedades Mecânicas.

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LIST OF ABBREVIATIONS

ABNT	Associação Brasileira de Normas Técnicas
ANOM	Analysis of means
ANOVA	Analysis of variance
BUE	Built up edge
CAPES	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
CBN	Cubic Boron Nitride
CF	Carbon Fibers
CFRE	Carbon fiber reinforced epoxy
CFRP	Carbon fiber reinforced polymers
CVD	Chemical Vapour Deposition
DOC	Depth of cut
E732	Composite Toray E732 [®] with snap cure toughened epoxy resin matrix
FFD	Full factorial design
GFRE	Glass fiber reinforced epoxy
GFRP	Glass fiber reinforced polymers
HRC	Hardness Rockwell C
HSM	High Speed Machine
HV	Hardness Vickers
IES	Instituição de Ensino Superior
ISO	International Organization for Standardization
MRR	Material removal rates
NBR	Norma Brasileira Registrada
OM	Optic Microscopy
PCD	Polycrystalline Diamond
PVD	PVD Physical Vapour Deposition
RSM	Response Surface Methodology
SEM	Scanning Electron Microscope
TC910 PA6	Composite Toray Cetex [®] TC910 with Polyamide 6 matrix
TiAlN	Titanium Aluminium Nitride
TiCN	Titanium Carbon Nitride
TU DELFT	Delft University of Technology

LIST OF SYMBOLS

A_c	Cutting area
a_e	Radial depth of cut
AE	Acoustic emission
a_p	Cutting depth
C_s	Cutting speed
D_t	Cutting tool diameter
f	Feed
F_c	Cutting force
Fe	Iron
f_z	Feed per tooth
h	Chip thickness
n	Rotation (spindle-speed)
P_c	Power Consumption
R_a	Roughness average (center line average)
R_t	Maximum height of the profile
R_z	Average maximum height of the profile
S_{ut}	Ultimate tensile strength
T_g	Ultimate glass transition temperature
V	Volts
v_c	Cutting speed
W	Watts

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1 INTRODUCTION

Machining is one of the most widely used techniques for manufacturing components in the industry, due to the wide variety of processed materials, shapes and characteristics of components, dimensional accuracy and good surface finishes (SHOKRANI et al., 2012). However, since composites are materials formed by constituents that are so distinct from each other (matrix and fibers), their machining sometimes becomes quite complex, making it difficult to obtain good surface quality and precise dimensional and geometric tolerances (RAWLINGS, 2013).

Currently, it is practically impossible to manufacture an automotive structural component without undergoing some kind of machining process, whether for dimensional requirements or to obtain a surface finish required in the mechanical design. The behavior of composite materials when machining differs in many aspects from that of metals, being much more complex and difficult due to the non-homogeneous and anisotropic nature of composites, particularly in the case of reinforcement using highly abrasive fibers as carbon fibers. During the process, depending on the technique used, delamination, elastic recovery and matrix fracture may occur (ALTIN KARATAŞ; GÖKKAYA, 2018). In recent years, fiber-reinforced plastics have become a popular material for manufacturing components with high strength, stiffness, and lightweight, highly applicable to the automotive industry (KROLL et al., 2019).

Normally, defects and failures are reduced using unconventional manufacturing processes (ultrasound, laser, electro-erosion, water jet, plasma). However, when choosing these processes, the production cost highly increases, and thermal degradation and moisture absorption occur. To use conventional machining processes (e.g., milling, drilling and turning), advanced knowledge and control of the machining variables (i.e., machining parameters, tool geometry and type of machining) is required (CALLISAYA et al., 2023). The physical-chemical and mechanical properties of the composite, proportion and orientation of the fibers, type of matrix and reinforcement, method of obtaining the composite, thermal conductivity, among others, must be well known for the correct execution of the machining.

This work investigates the machining of composites based on thermoplastic and thermoset polymers in laminates plates by the means of asymmetric discordant milling process. Machining carbon fiber reinforced polymers (CFRP) materials has not proven to be trivial, requiring attention to defining the best parameters and machining cutting tools so as not to cause damage to the material, such as delamination and cracks.

This study was part of the broad context of the project “Ferramentarias brasileiras mais competitivas” of the Rota 2030 Mobility and Logistics program proposed by the Federal Government of Brazil, developed by a network of researchers involving four science and technology institutes, three tooling companies, a producer of structural components company and a vehicle manufacturing company. The project aimed to train national toolmakers in the design and manufacture of tools for processing composite materials for high-production rate applications.

These composite materials show great potential for reducing the weight of a vehicle's final structure. However, the major challenges in their use are precisely related to the early stage and finishing manufacturing processes, since a composite component may present regions with different thicknesses, complex geometries, different temperature gradients and thermal expansion coefficients, in addition to processing characteristics that require controlled heating and cooling of the manufacturing tools and control of machining processes applied.

The broad-spectrum of the project encompasses the main phases of tooling development and composite processing, including the stages of simulations, material selection, design, manufacturing, machining process and recycling of composite components. It should be noted that, the focus of this work is specific topic of machining process investigation.

The study of the machinability of thermoplastic and thermoset composite materials prioritizes the understanding of the behavior of the material during the milling process in order to verify the machinability of the material and the applicability of diamond-coated carbide tools, contributing to the development of solutions for machining these materials.

The content of this research work covers the following items: Chapter 2 details the study's main objective and each specific objective. Chapter 3 contains a review of the relevant literature to establish the theoretical framework, research gaps and current works in the area. The used materials and applied methodology are described in Chapter 4, after which the results are presented and discussed in Chapter 5. Subsequently, Chapter 6 outlines the main conclusions. Chapter 7 highlight both limitations to the study and recommendations for further researches.

1.1 SCOPE OF THE RESEARCH

For the investigation of the machining processing of carbon fiber reinforced composites, a thermoplastic matrix composite Toray Cetex[®] TC910PA6 and a thermoset matrix composite Toray E732[®] were subjected to milling machining. A detailed evaluation regarding

the identification of best cutting parameters (i.e., feed per tooth “ f_z ” and rotation “ n ”) and best type of cutting tools (material and geometry) was conducted. The aim to identify the best cutting conditions is to determine optimal machinability of both composites, providing best surface quality, reduction of failures and wear combined to a low processing cost. The machinability investigation was done after the machining of both TC910PA6 and E732[®] composite laminates considering the quality of the machined surfaces, occurrence of delamination and fiber breakage. As well as surface finish by roughness analysis (R_a , R_z and R_t). Milling machining tests were performed to monitor and identify the influence of the cutting parameters on the power consumption, vibration of the system, the wear and damage of the cutting tools and the quality of the machined surfaces. Statistical treatment was applied to all output variables of the process, including the analysis of variance (ANOVA), analysis of means (ANOM), signal to noise analysis (S/N) and comparative and normality tests.

The performance of the different materials and geometries of cutting tools was investigated considering main types of wear and damage their formation mechanisms.

After the definition of most suitable type of cutting tool and amplitude of cutting parameters for each composite material, an optimization study was applied to verify accuracy of parameters range within the best region of application, as well as the predictability of process output variables by applying the statistical and mathematical techniques of the Response Surface Methodology (RSM).

Lastly, a study was applied to investigate the influence of machining parameters in the mechanical integrity of machined composite surfaces. The effects of machining on the mechanical properties of the composite materials were analyzed by evaluating disparities in the mechanical responses considering static tests (i.e., tensile and static bending) and dynamic tests (i.e. axial fatigue and 3-point fatigue bending). The investigation of the machining parameters effect on the mechanical properties was carried out in the Delft Aerospace Structures and Materials Laboratory (DASML) of the Delft University of Technology (TU DELFT) - Department of Aerospace Structures & Materials - located in the city of Delft, Netherlands.

1.2 JUSTIFICATION OF THE RESEARCH

The work is justified due to the current context of low technological and economic competitiveness of national tooling industry and the need to develop technologies in new materials to meet the energy efficiency and structural performance requirements of the automotive sector, especially considering the application of composite materials in this sector.

This project foresees the development and application of methodologies for machining composite materials. As described in the presented project, the automotive industry finds in composites a good alternative of materials for structural use, due to the possibility of reducing the total weight of vehicles, increasing safety and reducing fuel and emissions costs. It is known through the state of the art that the development of the processing of composite materials for high production rates has low technological maturity, due to the various challenges that make up the machining and processing of these materials, requiring greater advances so that composite components become economically and technologically viable products.

To ensure the assertive application of cutting parameters, the study of influence of cutting conditions on the mechanical performance of composite laminates will contribute to the robustness of the machinability analysis. The mechanical integrity is essential in structural components and machining processes are denoted by high dynamic cutting and temperature stresses that can induce efforts and trigger failures and changes the integrity of machined materials, thus altering their mechanical properties. For this motive, the study of the influence of process cutting parameters on the mechanical performance developed in the TU DELF is essential to assure reliability of results and optimal machinability.

Therefore, in general terms, this project promotes gains in knowledge of the machinability of the thermoplastic and thermoset composite materials reinforced with carbon fibers, which will allow overcoming the main challenges related to the manufacture of composite parts and the production of tools for their processing.

1.2.1 Originality / Novelty of the research

The originality of this work is highlighted in the investigation of the machining process of highly applicable composite materials specifically for structural applications in the automotive industry which presents several difficulties that require an in-depth study of all the phenomena occurring during the process. The machining is applied to high thickness composites laminates (>4mm) specific for structural components. Since the structural parts are responsible to around 60% of a vehicle's weight (MALLICK, 2010), its study and conversion from metallic to composite structures presents the best opportunity to weight reduction. Structural implementation of composite components imply in progressive increase of resistance to efforts, vibrations and mechanical integrity hence the importance of surface quality and machinability control and optimization. Nonetheless, as most of studies contribute to aeronautic and aerospace improvements in composites application, the automotive area present a way to

explore key opportunities for metal-to-plastic conversion and weight reduction capabilities that can improve performance in vehicles.

In addition, the study of composites with both thermoset and thermoplastic matrix reinforced with carbon fibers allows a robust investigation with comprehensive understanding of the behavior of each composite material during and after the machining process and the matrix influence into the mechanisms that govern the cutting dynamics during machining, highlighting their similarities and disparities that can promote lower cutting resistance, high material removal and viability of use. Each matrix can have its advantages (e.g. impact energy absorption, ability to post-form, low moisture absorption), which can benefit mechanical and structural integrity.

The studied laminates were manufactured with hot compression molding process that characterizes a practical approach of manufacture assuring cost-effectiveness and precision in manufacturing reducing voids and promoting homogeneous dispersed fibers (MAZUR et al., 2016).

Moreover, the definition of the optimal conditions and trends for composites in milling machining contributes to improve the machining by highly applied industrial process that enable a wide range of component geometries combined to strict dimensional tolerances.

Therefore, the gained knowledge about the machining process by evaluating the defects inherent in the manufacture of these materials, in addition to the study to reduce costs and losses, with an evaluation of all process output variables, developing methodologies to predict trends in the machining of composite materials, thus aiming to enhance the competitiveness of the national tooling industry on a global level in this disruptive topic that is still in its early stages in several research groups around the world. In addition, the work determine the optimal conditions for carrying out the process through the application of statistical tools, in addition to the establishment of trends and machining ranges, which could provide great gains and industrial application.

1.3 RESEARCH QUESTION AND HYPOTHESIS

Due to the complexity of analyzing the machining composite materials reinforced with abrasive fibers, and since the work evaluates not only the machinability of the composites, but also the choice of cutting tools and the surface and mechanical integrity after the machining process, the research work has the following main and specific research questions:

Table 1 – Research questions and hypothesis regarding the machinability of the composites Toray Cetex[®] TC910PA6 and Toray E732[®].

(Continue)

Type	Research question	Hypothesis
Main	Which are the most suitable conditions to machine the composite materials by milling?	The conditions will vary according to the composition of the composite matrix and its manufacturing. In general, thermoplastic based CFRP tend to facilitate cutting in intermittent processes such as milling.
Specific	Is there significant influence of the input variables of the process (cutting parameters) in the output variables (power consumption “P _c ”, acoustic emission “AE”, vibration, surface quality and tools wear) for milling each composite?	The cutting parameters will influence the output variables within distinct levels of significance and relevance.
Specific	What was the final surface quality?	Roughness results will be within standard amplitudes to machine CFRP (rough and finishing machining).
Specific	Is there a correlation between the effects resulting from machining and the surface integrity?	Delamination and other failures can be favored in discordant and intermittent machining processes.
Main	What is the impact of material and geometry of cutting tools in the composite’s machinability?	The material and coating of carbide tools will likely affect its performance. Diamond coated tools tend to reduce delamination in composites.
Specific	Is there a preferential geometry that allows reduction of wear or improvement in surface quality?	Multiple cutting edges tend to easy cutting forces for tangential milling. However discordant cutting can be negatively affected.
Main	Is it possible to optimize the cutting parameters determination within best application ranges and estimate trends as well predictability of output variables?	The RSM allows the verification of value range accuracy of parameters and estimates optimum high and low boundaries that can improve cutting parameters application.

Table 1 – Research questions and hypothesis regarding the machinability of the composites Toray Cetex[®] TC910PA6 and Toray E732[®].

(Conclusion)

Main	<p>Which optimal combined conditions (cutting tools and cutting parameters) are applicable to best machine the composites ensuring minimization of effects that induce damage to the surface integrity and performance of the materials after machining?</p>	<p>Optimal cutting conditions will consider best response in following outputs (in order): Surface quality, surface integrity, vibration, mechanical behavior and power consumption.</p>
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Source: The Author.

Table 2 – Research questions and hypothesis regarding the mechanical integrity study after machining of the thermoplastic matrix Toray Cetex[®] TC910PA6 and the thermoset matrix Toray E732[®].

(Continue)

Type	Research question	Hypothesis
Main	Does the machining conditions change the material's static behavior?	The static response is not likely to be affected by machining parameters change with the use of same geometry and material of cutting tool.
Specific	Does the machining parameters influence the ultimate tensile strength?	The ultimate tensile strength is not affected by the machining parameters.
Specific	Is there any change in strain evolution due to machining?	The macroscopic strain evolution should not change with the machining parameters.
Specific	Is there any difference in the damage evolution captured by the acoustic emission?	The damage monitored by the acoustic emission may change with machining parameters. The AE will support main findings to static behavior investigation.
Main	Does the machining conditions change the material's dynamic behavior?	The dynamic response is highly dependent on the surface quality as result of machining conditions.
Specific	What is the influence of machining parameters on the fatigue life for each stress level?	The machining parameters influence the fatigue life, and the response may be affected by the stress level.

Table 2 – Research questions and hypothesis regarding the mechanical integrity study after machining of the thermoplastic matrix Toray Cetex[®] TC910PA6 and the thermoset matrix Toray E732[®].

(Conclusion)

Specific	Is the hysteresis ratio maintained for the different machining conditions and stress levels?	The total dissipated energy and total work can be altered by machining conditions.
Specific	Is there significant difference in fatigue behavior to low and high stress levels?	Lower stress levels could enhance the perception of change in fatigue behavior.
Main	Does the machining conditions change the material's flexural behavior?	The flexural behavior may be affected by machining parameters.
Specific	Does the machining change the maximum Flexural stress for each condition?	The machining parameters should have little impact.

Source: The Author.

6 CONCLUSIONS

The conclusions obtained with the machinability analysis of the thermoplastic matrix composite Toray Cetex® TC910 PA6 and the thermoset matrix composite Toray E732® relative to the analysis of the input and output variables of the milling machining process are:

- The thermoset matrix composite Toray E 732® presented higher incidence of discontinuous fiber rupture during machining that favored more pronounced lateral delamination type II when using high feed per tooth values (0.075 and 0.10 mm/t). In addition, several regions of porosity were observed in the lateral region and discontinuous distribution of fibers that led to increased roughness.
- The thermoplastic matrix composite Toray Cetex® TC910 PA6 presented lower occurrence of transient vibration peaks during the process to all studied signals, as well as a lower power consumption amplitude in the dynamic behavior analysis. The most influential parameter for the milling process was the feed per tooth f_z , with a better surface finish achieved with the application of a feed of 0.025 mm/t.
- The amplitude of power consumption was critically dependent to the change of cutting tool geometry. The multi-edge cutting tool with diamond coating (ME-D) led to power consumption ranges that reached 4 times the average value of helical cutting tools.
- The acoustic emission response obtained was within the range of finishing machining CFRPs. However, the variation presented low values to provide detail about the influence of cutting parameters variation for both materials. There is indication of acoustic emission association with chip formation during the milling machining process. A correlation study considering other dynamic signal responses is advised to address the AE tendencies.
- The multi-edge geometry of cutting tools also resulted in higher amplitudes of roughness R_a , as well to the occurrence of cutting edge failures as micro-chipping (observed to the ME-D geometry). The multi-edge profiles are not indicated to finishing machining both CFRPs tested. These geometries might be indicated to higher depths of cut and rough machining.

- The employed detailed statistical analysis of ANOVA and ANOM combined with comparison and normality tests (Tukey and Anderson-Darling tests) were proven to provide fundamental basis of data tendency, analysis of means, dispersion and aid the definition of best cutting parameters selection.
- The Signal-to-noise ratio analysis provided an accurate variability estimation for each tested conditions as well as the ranking of most influential factor to each evaluated response of the process. The S/N analysis was a secure technique of practical use, to monitor the data scattering and robustness of machining both materials.
- In milling, the most frequent observed delaminations types were type II and type I/II combination. Type II delamination can be attenuated by increase in rotation during the cut in finishing machining regimen. The brittle behavior of the cross-linked structure of the thermoset composite led to higher efforts in machining, edge breakage and chipping as well as delamination progression.
- Helical tool geometry provided better chip evacuation and surface finish, making them ideal for finish machining. Multi-edge tools, with their several distributed cutting edges created localized fiber fracturing, leading to powdery chips and increase in cutting forces. The LH tool can promote gradual fiber shearing, reducing splintering and improving chip evacuation that could have been responsible of enhancement of surface finish. A beneficial effect on chip formation mechanism of shearing was achieved with the left-helix tool.
- The chips generated in the milling process changed with the composition of the matrix of the composite. Small particulate fracture chips were observed to the thermoplastic matrix composite Toray Cetex[®] TC910 PA6. The abrasiveness of CF reinforcement region was responsible for chip detachment of the cutting region. Powdery particulate chips were observed to the thermoset matrix composite Toray E732[®]. The epoxy matrix was most responsible for the type of chip formation. Closed-system collection of chips is advised to ensure safety in the thermoset E732 composite machining.
- Optimized cutting conditions to the thermoplastic matrix composite Toray Cetex[®] TC910 PA6 are reduction of feed per tooth and LH cutting tool application as supported by the response surface methodology.

The conclusions obtained with the investigation of the milling machining parameters effect on the static and dynamic mechanical properties of the thermoplastic matrix composite Toray Cetex[®] TC910 PA6 and thermoset matrix composite Toray E732[®] composite with M1 ($f_z = 0.02$ mm/t ; $n = 4000$ rpm) and M2 ($f_z = 0.10$ mm/t ; $n = 7500$ rpm) conditions are:

- The milling machining process did not reduce the static mechanical strength of the composite. In addition, the slight increase in the order than less than 5% may imply similar static properties for all conditions for the thermoplastic matrix composite Toray Cetex[®] TC910 PA6.
- The S-N curves for the neutral and M2 conditions are nearly similar for all tested stress levels, which indicates that the dynamic properties of the thermoplastic composite were maintained after milling with $f_z = 0.10$ mm/t and rotation= 7500 rpm.
- Machining can impact the fatigue performance depending on the process parameters. Milling with the M1 machining parameters resulted in delamination, which reduced the fatigue life for high stress levels. Another point that supports that the damages could be responsible for the change in the dynamics properties is that the calculated hysteresis ratio was similar to M1 and M2 conditions, which indicates that the material is homogeneous for both conditions.
- The results showed that the fatigue life was similar for all conditions at the high cycle fatigue regime (low stress regime), indicating that the milling process could be applied to the material maintaining the fatigue properties and structural integrity. To mitigate the impact of machining on the machining properties, optimized machining parameters can be employed.
- The higher rotation applied to the M2 machining condition might have reduced burr formation and delamination type I and type I/II that minimized the impact in dynamic properties in this condition.

7 RECOMENDATIONS FOR FUTURE RESEARCH

Progress have been made to improve the knowledge of the machinability response of CFRP_s during and after the milling process. The results of this research work also provided contribution to evaluate the machining impact in the mechanical properties of CFRPs. However, there are many points for future research to improve the main findings and address to the research area. As regarding the topics to build upon the work main findings, the in-deep investigation of following items is suggested:

- *Morphology study of chips*: As considering the complex formation of composites chips SEM images could be applied to better identification of formation mechanisms and correlation between the mechanism and the region of cut (matrix or reinforcement).

- *Change the cutting regime for milling*: Even though the applied multi-edge tools did not favor surface quality in terms of roughness R_a in the regimen of finishing machining, there are indications that this profile could work for rough milling. An exploratory study could provide guide directions to verify this profile viability for rough machining.

- *Improve the AE analysis for machining*: The acoustic emission analysis in machining CFRPs is complex to evaluate. A study considering minimal and average amplitudes of AE in contrast to only the maximum results during machining could be beneficial to better understand the phenomena during the cut. In addition, signal processing by mathematical tools (i.e. wavelet transforms as function or filters) could improve the signal workability allowing correlation to the process. Moreover, the isolation and definition of specific acoustic emission frequency spectra and waveforms are emitted in the cutting zone for different tool wear would provide a better understanding and correlation to the machining.

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DADOS CURRICULARES

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PRODUÇÃO BIBLIOGRÁFICA	
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SILVA, G. A. M.; SCHNEIDER CALLISAYA, EMANUELE; FERNANDES, M. F.. Participação em banca de ANA CAROLINA AQUINO PEREIRA. **ANÁLISE DA INFLUÊNCIA DA ROTAÇÃO NO PROCESSO DE BRUNIMENTO DAS LIGAS DE ALUMÍNIO 2024 T851, 6061 T651 E 7050 T7451 TRATADAS SUPERFICIALMENTE COM ANODIZAÇÃO SULFÚRICA DURA**. 2025. Trabalho de Conclusão de Curso (Graduação em Engenharia de Materiais) - Universidade Estadual Paulista Júlio de Mesquita Filho.

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BARBOSA, F. P.; SCHNEIDER CALLISAYA, EMANUELE; SOUZA, J. V. C.. Participação em banca de Felipe de Paula Barbosa. **Análise da Implementação da Logística Reversa na Indústria Farmacêutica no Brasil**. 2022. Trabalho de Conclusão de Curso (Graduação em Engenharia de Materiais) - Universidade Estadual Paulista Júlio de Mesquita Filho.

MONTEMOR, M.; SCHNEIDER CALLISAYA, EMANUELE; ALVES, M. C. S.; SOUZA, J. V. C.. Participação em banca de Mateus Montemor. **Análise do torneamento do aço ABNT 8620 com ferramentas de metal duro revestidas por Ti (C, N) + Al₂O₃ e TiAlSiN**. 2022. Trabalho de Conclusão de Curso (Graduação em Engenharia Mecânica) - Universidade Estadual Paulista Júlio de Mesquita Filho.

CAMPOS, V. H. A. E.; SCHNEIDER CALLISAYA, EMANUELE; ALVES, M. C. S.. Participação em banca de Vitor Hugo de Andrade e Campos. **Estudo e aplicação da Norma Regulamentadora N°12 em uma máquina produtora de semiacabado para curativos adesivos**. 2022. Trabalho de Conclusão de Curso (Graduação em Engenharia Mecânica) - Universidade Estadual Paulista Júlio de Mesquita Filho.

GOMES, R. A.; SCHNEIDER CALLISAYA, EMANUELE; ALVES, M. C. S.. Participação em banca de Rodrigo Anginho Gomes. **Análise da ferramenta de metal duro com recobrimento de Ti(C,N) + Al₂O₃ no torneamento do metal AISI 4340**. 2022. Trabalho de Conclusão de Curso (Graduação em Engenharia Mecânica) - Universidade Estadual Paulista Júlio de Mesquita Filho.

CALLISAYA, E. S. ALVES, M. C. S. Participação em banca de Beatriz de Oliveira Garcia. **Estudo do torneamento do aço 4340 com ferramenta de metal duro recoberta por TiCN+Al₂O₃**. 2021. Trabalho de Conclusão de Curso (Graduação em Engenharia de Materiais) - Universidade Estadual Paulista Júlio de Mesquita Filho.

CALLISAYA, E. S. ALVES, M. C. S. Participação em banca de Larissa Manucci. **Análise comparativa de diferentes recobrimentos de ferramentas de metal duro no torneamento do aço AISI 52100**. 2021.

CALLISAYA, E. S. ALVES, M. C. S.. Participação em banca de João Guilherme Domingues. **Anodização Dura Em Pistões de Alumínio**. 2021.

ALVES, M. C. S.; CALLISAYA, E. S. ALVES, M. C. S. Participação em banca de Vivian Martins Ferreira da Silva. **Análise do torneamento do aço AISI 4340 endurecido com ferramentas de metal duro recobertas com TiAlN+TiN**. 2020. Trabalho de Conclusão de Curso (Graduação em Engenharia de Materiais) - Universidade Estadual Paulista Júlio de Mesquita Filho.

CALLISAYA, E. S. ALVES, M. C. S.. Participação em banca de GABRIEL AUGUSTO MALVÃO SILVA. **Influência da rotação no processo de brunimento do alumínio A357.0 T6 utilizando réguas abrasivas de diamante**. 2020.

CALLISAYA, E. S.; ALVES, M. C. S.. Participação em banca de Nicolas da Paixão Mota. **Estudo do efeito de diferentes ferramentas e ângulos de posição no torneamento do eucalyptus sp**. 2020.

CALLISAYA, E. S.; SOUZA, J. V. C.. Participação em banca de Pedro Henrique Imerglik. **Desempenho da ferramenta de metal duro com filme de nano diamante para usinagem de alumínio 6005A**. 2020.

CALLISAYA, E. S. ALVES, M. C. S. Participação em banca de Pedro Imerglik.

Desempenho da ferramenta de metal duro com filme de nano-diamante para usinagem de alumínio 6005A. 2019.

ALVES, M. C. S.; CALLISAYA, E. S.. Participação em banca de Felipe Brandino. **Projeto de um alimentador pneumático de matéria prima para um centro de usinagem três eixos.** 2019.

Orientações

Carlos Eduardo da Silva Francisco. **Estudo da influência dos parâmetros de corte e da estrutura química do material no fresamento de compósitos reforçados com fibra de carbono.** 2023. Trabalho de Conclusão de Curso. (Graduação em Engenharia Mecânica) - Universidade Estadual Paulista Júlio de Mesquita Filho. Orientador: Emanuele Schneider Callisaya.

Rafael Kenji Suguita. **Análise da furação de compósitos reforçados com fibra de carbono utilizando brocas com diferentes ângulos de ponta.** 2022. Trabalho de Conclusão de Curso. (Graduação em Engenharia de Materiais) - Universidade Estadual Paulista Júlio de Mesquita Filho. Orientador: Emanuele Schneider Callisaya.

PARTICIPAÇÃO EM EVENTOS CIENTÍFICOS

IX Workshop de Pós-graduação em Engenharia. Fresamento de Compósitos Reforçados com Fibra de Carbono: Desafios, Estratégias Sustentáveis e Contribuições para Aplicações Estruturais Avançadas. 2025. (Congresso).

12º Congresso Brasileiro de Engenharia de Fabricação COBEF 2023. Investigação do processo de fresamento de CFRPs termoplásticos utilizando o método de otimização de Taguchi. 2023. (Congresso).

14th International Conference on the Mechanical Behaviour of Materials. Analysis of power consumption during the machining of epoxy based CFRP. 2023. (Congresso).

27th International Congress of Mechanical Engineering COBEM 2023. Process analysis in the drilling of carbon fiber reinforced composite using different point angles of twisted drills. 2023. (Congresso).

VII Workshop da Pós-graduação em Engenharia. 2023. (Congresso).

VI Workshop da Pós-Graduação em Engenharia. Estudo da variabilidade do processo de usinagem de compósitos reforçados com fibra de carbono. 2022. (Congresso).

11th Brazilian Congress on Manufacturing Engineering COBEF. Effect of machining parameters on chip formation in dry-milling of the nickel based superalloy VAT 32®. 2021. (Congresso).

26th International Congress of Mechanical Engineering COBEM 2021. Optimization of machining parameters in the dry milling of Ni-based VAT 32® superalloy with TiAlN-TiN coated carbide inserts. 2021. (Congresso).

V Workshop de Engenharia Mecânica e de Produção FEG UNESP. Recentes desenvolvimentos no processo de manufatura de compósitos de alta cadência para a indústria automobilística. 2021. (Congresso).

XXXIII Congresso de Iniciação Científica da Unesp. Avaliação de Trabalhos. 2021. (Congresso).

IV Workshop de Engenharia Mecânica e de Produção da FEG-UNESP - Edição Online. Análise da potência de usinagem no fresamento da superliga VAT 32® com ferramentas de metal duro recobertas com TiAlN-TiN. 2020. (Congresso).

25th International Congress of Mechanical Engineering COBEM 2019. Surface quality and tool wear analysis on the turning of hardened AISI 4340 steel using experimental ceramic cutting tools. 2019. (Congresso).

III Workshop de Engenharia Mecânica e de Produção. Análise da vibração no fresamento da superliga VAT32® com ferramentas de corte de alumina com diferentes dopantes. 2019. (Outra).

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XXX Congresso de Iniciação Científica da UNESP. Análise do desempenho de ferramentas cerâmicas Al₂O₃+MgO e de PCBN no torneamento do aço AISI 4340 endurecido. 2018. (Congresso).

XXIX Congresso de Iniciação Científica da UNESP. Análise do desempenho de ferramentas cerâmicas no torneamento do aço AISI 4340 endurecido. 2017. (Congresso).

XXVI Congresso de Iniciação Científica da UNESP. Qualidade superficial e esforços no fresamento do aço SAE 4340 com a técnica de mínima quantidade de fluido. 2014. (Congresso).

XXV Congresso de Iniciação Científica da UNESP. Sistema de Irrigação inteligente para Cultivo Protegido. 2013. (Congresso).