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Research Article

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Posted Date: June 24th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10046715/v1>

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Additional Declarations: No competing interests reported.

DEVELOPMENT OF COMMINGLED HOOP-WOUND COMPOSITES REINFORCED O-RINGS (CRO) FOR AERONAUTICAL APPLICATION

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ABSTRACT

Traditional elastomeric O-rings, although widely employed in aerospace sealing applications, are often limited by its inadequate chemical resistance, thermal stability, mechanical resistance and durability under extreme operating conditions. This article proposes the development of high-performance composites for O-ring reinforcement using carbon fiber/polyether ether ketone and glass fiber/polyamide commingled technologies engineered to address current limitations by integrating elastomeric materials with continuous reinforcements tailored for the demanding environments of aerospace systems. A novel pre-compaction device (machine head) for commingled tows was designed and developed for using at filament winding technique, which was used to manufacture the reinforcement inner section of the O-rings. Final compaction level of commingled composites was carried out using compression molding to meet aeronautical requirements. The materials were characterized by SEM and thermal analysis as DSC. O-ring reinforcements made from 3D-printed carbon fiber/Onyx and glass fiber/Onyx by Markforged® printer were also manufactured and tested, indicating the improvement of O-rings performance when used commingled technology. Using 3D-printing resources, a hermetic mold was created to combine the composites reinforcement with the silicon-based elastomeric covering. Finally, composites reinforced O-rings were submitted to tensile testing, based on ASTM D2290 procedures, and a comparison of the resulting mechanical properties revealed superior performance of the commingled reinforcements.

Keywords: Composite O-rings, 3D printed composites, filament winding, commingled technology.

1. INTRODUCTION

O-rings are one of the most reliable and versatile sealing solutions used in aeronautical industries. Designed to keep out environmental contaminants, retain essential fluids, and reduce friction between two mating surfaces, O-rings play a vital role in ensuring mechanical stability and operational efficiency of hydraulic and pneumatic systems. However, in the aerospace and aeronautics industry these components need to perform much more demanding functions. Aerospace O-rings are required to endure extreme conditions as high pressure, wide temperature fluctuations, and exposure to aggressive chemicals, while maintaining a precise seal ¹.

An O-ring functions by filling the space between two components, ensuring no fluid or gas escapes during operation. In aerospace applications, the margin for error is minimal, making quality, precision, and reliability critical. These O-rings are used in airplanes, helicopters, spacecraft, flight controls, landing gears, wheels, brakes, engines, and even cabin interiors ². Suitable materials for these demanding applications include ethylene propylene diene monomer (EPDM), silicon, nitrile rubber, fluoroelastomer (FKM), and polytetrafluoroethylene, each chosen based on the seal's location, temperature exposure, and fluid compatibility ³. Testing for fluid resistance, temperature range, tensile strength, and compression set is essential to guarantee performance and safety ⁴.

O-ring used on aerospace applications is quality-marked and batch-traceable, ensuring compliance with strict industry regulations. This traceability not only enhances accountability but also allows for the identification of any potential defects, maintaining the integrity of critical aerospace systems ⁵. Advancements in materials and manufacturing have been producing O-rings capable of sustaining extreme conditions without compromising elasticity or performance, even when composite materials are incorporated to them.

In addition, O-rings must withstand intense mechanical stress, high and low pressure, and exposure to fuels, oils, and deicers ⁶. These components are indispensable for maintaining hydraulic pressure, managing airflow, and ensuring consistent fuel containment during flight. The ability to provide a durable, leak-tight, and secure seal provides greater safety, efficiency, and

longevity to aerospace systems. With technological advancements in materials, rigorous testing, and proper installation, sealing rings continue to be the foundation of reliability in modern aviation and space exploration ⁷.

Composite reinforced O-rings (CRO), proposed in this study, emerged to combine flexibility of elastomeric seals with the strength and thermal stability of advanced composite materials, which meet the requirements and needs of aerospace sealing components. The development of the hybrid structure presents a novel solution for aeronautic applications, in which hoop-wound commingled composites produced by a filament-winding process are incorporated into elastomeric seals, creating a product that enhances system reliability, reduces maintenance frequency, and improves overall safety.

2. THEORICAL BACKGROUND

Thermoplastic polymers usually recognized by their ability to soften and melt upon heating and solidify upon cooling, considering an entirely physical and reversible process ⁸. This behavior allows thermoplastic materials to be suitable for thermoforming applications without significant degradation in their chemical structure, once the degradations limits are respected ⁹. The recent use of thermoplastic matrices in long-fiber composites has significantly enhanced several characteristics of these materials.

The main benefits of continuous fiber thermoplastic composites include the increased strength, damage tolerance, and durability of the composite components under extreme thermomechanical conditions. Furthermore, these improvements make thermoplastic composites more effective and reliable for a variety of high-performance applications ¹⁰. The significant reduction in processing time, compared to techniques used in thermoset matrix composites, is also one of the main advantages of thermoplastic composites, which not only contribute to cost efficiency but are also aligned with growing environmental concerns, promoting sustainability and reducing waste in manufacturing processes ¹¹. Additionally, thermoplastic composites exhibit significantly higher corrosion resistance compared to thermoset composites ¹².

In this context, the commingled technology, which combines thermoplastic yarns and continuous reinforcement fibers within a single tow ¹³, can be applied to CRO, offering significant advancements for this application despite processing challenges and the difficulty of controlling

the thermal and dimensional stability of the polymer ¹⁴, considering the size and shape of the component being produced. Defining the appropriate processing method for commingled composites requires a careful analysis of the characteristics and properties of the raw materials, along with a comprehensive understanding of the processing parameters as time, temperature and pressure.

The performance of CRO depends on controlling processing conditions in the inner composite reinforcement, the properties of the raw material, and the ability to achieve efficient fiber impregnation and adhesion. Scientific and technological studies on commingled materials aim to address existing barriers, such as the high viscosity of molten polymer which hinders proper impregnation of reinforcing fibers ¹⁵. The goal of improving the performance, efficiency, and scalability of thermoplastic composites for CRO in aeronautical applications ¹⁶.

The final consolidation of the hoop-wound a thermoplastic composite material depends on the process of compacting the its layers by compression molding to unify the material, reducing voids content and achieving the defined shape ¹⁷. This process involves the application of heat and pressure to ensure proper impregnation of the fibers with the matrix, resulting in a strong, cohesive composite structure with the desired mechanical properties ¹⁸. The impregnation process consists of pressing the molten polymer through the reinforcement in four main stages: polymer percolation through the fibers, flow of the molten polymer along the reinforcement plane, interlaminar shearing in the fiber direction, and interlaminar sliding between layers oriented differently ^{19,20}.

The inner CRO reinforcement considered the versatility of commingled technology, which enable precise unidirectional fiber alignment during the filament winding process. As a result, the mechanical properties can be tailored to meet specific requirements, such as enhanced tensile strength ²¹. Additionally, this technology helps reduce processing time and material waste, since the fiber and matrix are combined into a single filament, and the process is more precise than traditional fiber lay-up or prepregging methods ²².

However, commingled composite components may face challenges with an inadequate adhesion between layers, leading to issues with permeability, particularly the difficulty of molten material penetrating the fibers. This is partly due to the fact that molten thermoplastic resins have significantly higher viscosity compared to thermosetting resins, making it harder for the material to flow and properly wet the reinforcing fibers ²³. Some scientific studies were consulted to adapt

the filament winding process for manufacturing the inner reinforcement of CRO. A novel machine head was design and developed for this purpose.

The study conducted by Song *et al.* (2022) ¹⁶ proposed an Automated Fiber Placement (AFP) for in-situ consolidation of high-performance thermoplastic composites for continuous fiber-reinforced thermoplastic prepregs ²⁴ that resembles the processing mechanism required for commingled tows, and consequently, for producing the inner reinforcement of CRO. The process involved an automated placement equipment that consolidates the fibers using a compaction roller and laser induction. In accordance with the filament deposition mechanism described in this article, the fabrication of inner reinforcement for CRO consists of components, built layer by layer in the thickness direction until the desired thickness is achieved. The authors suggest that this technology is poised to revolutionize composite fabrication for aerospace applications by optimizing production and enhancing material performance. Also, the compaction provided by a roller must be used on thermoplastic composites processing. Similarly, Ueda *et al.* (2022) ²⁵ reported that the heater roller compacts the deposited filament layers, thereby reducing voids formation. However, this method increases the complexity of the system, which must maintain the compacting roller perpendicular to the direction while in motion.

Hoop-wound composite rings coated with high density polyethylene (HDPE) were tested using compression test fixture and analysis method by Kugler and Moon (2002) ²⁶. The study involved hoop-wound reinforcement ring made of Thornel T300 carbon fiber and Udel® P1700 polysulfone (PSF) as polymer matrix. Using a test device, the reinforced O-rings were subjected to a compressive axial load to produce hydrostatic pressure on the outside of the rings. Through Poisson's effect, the test causes the flexible (coating) ring to expand radially inward, compressing the composite ring. The test revealed that the reinforced O-rings failed due to the formation of a band that initiated on the outer surface and propagated radially, resulting in catastrophic failure immediately follow by a sharp drop in load.

In the context of the aerospace industry, commingled tows for 3D printing provide a powerful method for producing high-performance composite parts with tailored mechanical properties ²⁷. By combining continuous fibers with a thermoplastic matrix, this technology enables the production of lightweight, strong, and durable components for various industries, including aerospace, automotive, and sports equipment. While challenges persist in terms of fiber-matrix

bonding and processing, the potential benefits of commingled tow in 3D printing are significant, particularly for custom and high-performance applications.

The difficulty in processing these materials also includes the challenge of controlling the thermal and dimensional stability of the polymer, which can vary depending on the size and shape of the component being produced ²⁸. Therefore, the appropriate processing method must consider both the characteristics and properties of the raw material, as well as a thorough understanding of the thermoplastic composite component to be manufactured. This ensures optimal processing conditions and the desired quality of the final product. Consequently, AM techniques also present the same challenges related to the processing of thermoplastics. The success of AM with commingled thermoplastics tows depends on controlling processing conditions, material properties, and the ability to achieve efficient fiber impregnation and adhesion.

Kanahan *et al.* (2024) ²⁹ developed a study which different thermoplastic matrices for composites were compared, establishing the optimal processing parameters and conditions to improve mechanical performance when gains in processability and wettability are achieved. Later, Kanahan *et al.* (2025) ³⁰ studied the mechanical behavior of commingled thermoplastic composites with different reinforcements, including carbon, glass, linen, and hemp fibers. Overall, the research results highlighted how selecting different tailored composite properties for applications in aerospace industries, in accordance to the mechanical behavior obtained for each material.

Di Benedetto *et al.* (2017) ²¹ investigated the influence of thermal processing parameters on the mechanical properties of commingled composites, developing a methodology that incorporates thermal degradation limits and optimized processing models. The thermal degradation kinetics based on the model proposed by Friedman (1964) ³¹ was used to obtain rate laws and kinetic parameters that describe the thermal degradation of polymers from empirical data obtained through thermogravimetric analysis (TGA) ³². The method is based on the comparison of experiments conducted at different heating rates, making possible to determine the activation energy (E_a) attributed to the material's degradation.

The commingled composite manufacturing depends on the thermo-oxidative degradation limits provided by Friedman's isoconversional method ^{33,34}, in order to optimize the material mechanical properties. Thermogravimetric methods for evaluating the degradation kinetics of thermoplastic composites involve tests at different heating rates to plot the material's degradation limits, beyond the determination of E_a as a function of α . The peak temperature, T_{peak} , represents

the point at which the heat input equals the heat absorption ratio. These calculations can be used to define the processing window ³⁵ for thermoplastic composites, focusing on the time and temperature required for the polymer matrix melting without reaching a degree of degradation that would be harmful to the component being processed ¹⁷.

From this perspective, Di Benedetto *et al.* (2022) ¹³ conducted a design of experiments (DOE) analysis to correlate processing conditions with the mechanical properties of thermoplastic commingled composites, specifically carbon fiber/polyamide (CF/PA) and carbon fiber/polyether ether ketone (CF/PEEK). The impact of thermal consolidation on material performance was also evaluated and quantified, taking into account the thermal degradation limits and kinetics. The study's findings highlighted the optimal combination of variables that enhance the structural capabilities of commingled composites. Additionally, it was revealed that the mechanical properties of these composites are significantly influenced by the dispersion of polymer yarns within the carbon fiber tow, which was categorized into distinct distribution patterns.

Further, Di Benedetto *et al.* (2022) ³⁶ used CF/PEEK commingled tow to manufacture a hybrid composite structure, applying concepts and methodologies based on Friedman's method and Darcy's law to optimize the material's performance. The CF/PEEK commingled composite was mechanically characterized through interlaminar shear strength (ILSS) tests, which revealed a mean short-beam strength of 68.3 MPa. Therefore, based on the material's adhesion and bonding performance, this value serves as a reference for comparing further new 3D-printed composites.

The use of commingled tows in 3D printing offers several advantages, particularly for creating composite materials with enhanced properties. This technology improves the integration of fibers into the thermoplastic, resulting in low-porosity materials that enhance overall performance. A primary technical challenge is developing a single-step system for 3D printing, which would significantly reduce processing time and production costs, while enabling the fabrication of high-performance structures. Therefore, this work will first present the results of characterizing GF/PA and CF/PEEK commingled composites manufactured through compression molding. These results will establish the desired thermal, thermomechanical, and mechanical property values for future commingled CRO.

3. MATERIALS AND METHODS

Concordia Manufacturing, LCC has supplied the commingled tows used for the CRO inner reinforcement: carbon fiber/polyether ether ketone (CF/PEEK) and glass fiber/polyamide (GF/PA). According to the technical specifications, Toho-Tenax® carbon fibers (HTS40 T300 12k) have a tensile strength of 4240 MPa and an elastic modulus of 237 GPa³⁷. AGY Holding Corporation's E-glass fiber class have a tensile strength of 3445 MPa and an elastic modulus of 76 GPa³⁸. Furthermore, PEEK-900/68 should be processed from 360-400°C and the PA-900/72 from 240-290°C. The GF/PA commingled tow presents glass fiber volume content of 55.5% and has a relative density of 1.90 g/cm³, while CF/PEEK consists of 47.3% carbon fiber by volume and it has a relative density of 1.62 g/cm³.

The test to determine the reinforcing constituent content of the commingled tows was conducted using Method I of ASTM-D3171³⁹. Procedure A was used for CF/PEEK, where the matrix was removed by burnoff in a muffle furnace, while Procedure G was applied to CF/PA, which removes the matrix chemically through acid digestion (nitric acid).

The GF/PA and CF/PEEK commingled tows were first examined using SEM and optical miCROcopy to evaluate the diameters of the polymer yarns and reinforcement fibers, as well as the CROs-sectional diameter of each tow. SEM was conducted by a ZEISS EVO MA10 miCROcope and the optical analysis was performed by ZEISS Jenavert miCROcope.

The crystallization enthalpy and temperatures of the thermal events were determined using the DSC technique. The Q20 2151-TA Instruments calorimeter with the RCS40 cooling unit was employed for the thermal analysis of GF/PA and CF/PEEK. The DSC thermal cycles consisted of heating from 25°C to 250°C at a rate of 10°C/min, followed by cooling at a rate of 20°C/min. The analysis was conducted in a nitrogen atmosphere with a flow rate of 30 mL/min, following standard procedures outlined in ASTM-D3418⁴⁰.

Korthfiber 4-axis filament winding machine was used to wrap both CF/PEEK and GF/PA commingled tows. A flat metallic support, as used in other studies³⁶, accommodated the tows in a unidirectional arrangement to be later processed through thermal consolidation. The laminates must contain 3mm of thickness for test characterization, so the winding process involved 5 complete cycles of wrapping. Figure 1 shows the winding mechanism used to wrap CF/PEEK and CF/PA unidirectionally.

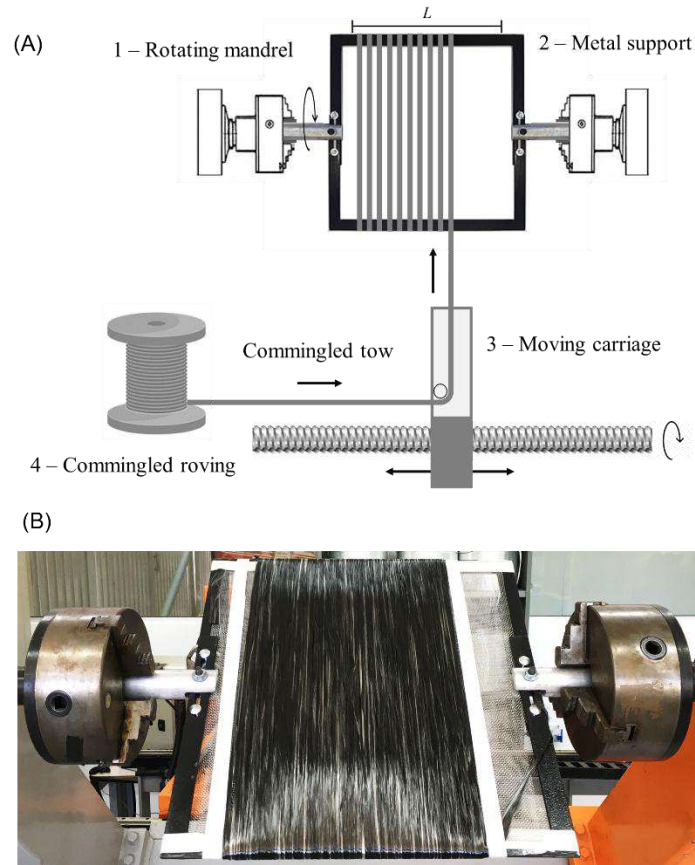


Fig. 1 - The filament winding mechanism was used to wrap CF/PEEK and GF/PA commingled tows, which were later processed using a heated hydraulic press. (A) schematic view of the filament winding system and (B) CF/PEEK commingled preform. (Adapted from ³⁶)

The consolidation pressure (P) was determined empirically in previous studies ^{21,32}, in which the Darcy's law was used and provided the processing parameters for the under pressure consolidation. Ultrasound inspections and SEM were used to identify the minimum value of P required to ensure laminate consolidation without defects aCROs the commingled composite CROs-section ¹³. For both CF/PEEK and GF/PA, $P=30 \text{ t/m}^2$ was sufficient for complete consolidation.

A Korthfiber 4-axis filament winding machine with a $\varnothing 86\text{mm}$ cylindrical rotating mandrel was used to produce both hoop-wound CF/PEEK and GF/PA CRO inner reinforcements. A novel machine head with a heating system was installed on the filament winding machine to ensure the preconsolidation of the stacked layers into the shape of the cylindrical mandrel. The heating system

consisted to a central heating thermostat controller. Initial tests indicated optimal compaction at 400°C for PEEK and 260°C for PA, a feed rate of 0.08 m/s (derived from the mandrel rotation), and 10 turns, resulting in hoop-wound commingled composites with a thickness of 3.2mm. Figure 2 shows the machine head developed and used on the fabrication of the CRO inner reinforcement by filament winding.

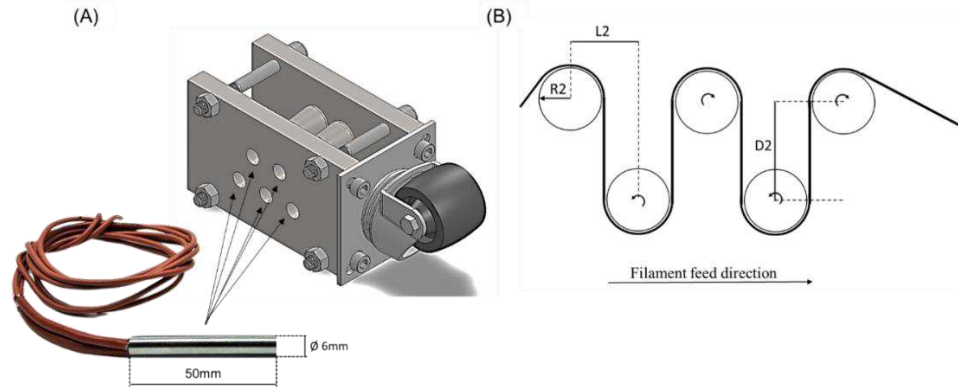


Fig. 2 - Designed machine head adapted on filament winding process. (A) 3D illustration drawing of the machine head indicating the location of the cartridge resistors, and (B) preconsolidation mechanism of commingled tows.

Table 1 presents the dimensions of precompaction roller radius (R2), the linear distance between the rollers (L2), the vertical misalignment distance (D2), the filament contact area with the heated rollers, and the linear speed of the preconsolidated commingled filament.

Tab. 1 - Dimensions of the machine head adapted on filament winding process.

Head design	Dimension				
	R2 (mm)	L2 (mm)	D2 (mm)	Contact heat area (%)	Linear feed rate (m/s)
1	4.35	8.10	11.90	50	0.08

Figure 3 reveals the production of the hoop-wound composites reinforced O-rings by filament winding. Next, it can be observed the machine head, the compaction system, the composite rings wound on the mandrel, and the reinforcement ring after demolding.

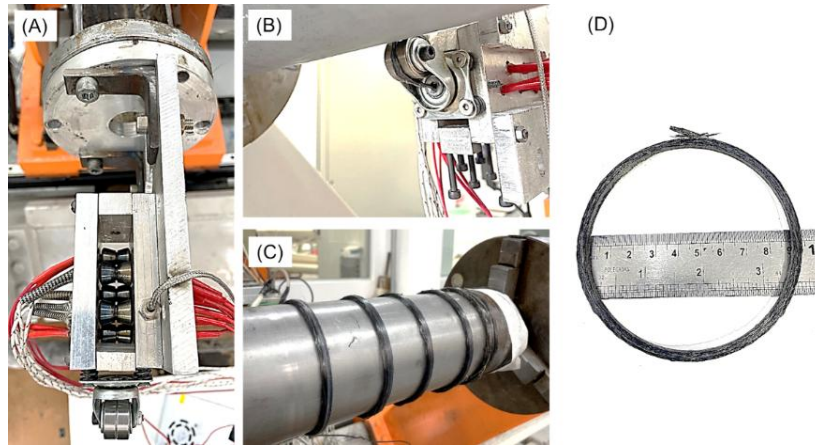


Fig. 3 - Manufacturing of the CRO' inner composite reinforcement. (A) heated machine head adapted on the filament winding machine, (B) detail of the commingled filament deposition, (C) hoop-wound composites after winding and (D) final aspect of the preconsolidated composite ring.

After produced the composite reinforcement, they were submitted to the compression molding for total compaction using a Solab SL hydraulic press under 30 t/m² of pressure at 400°C for CF/PEEK, and 260°C for GF/PA commingled composites. A metallic mold was design for attach and press the composite rings. Figure 4 reveals the compression molding of the composite rings used as CRO reinforcement.

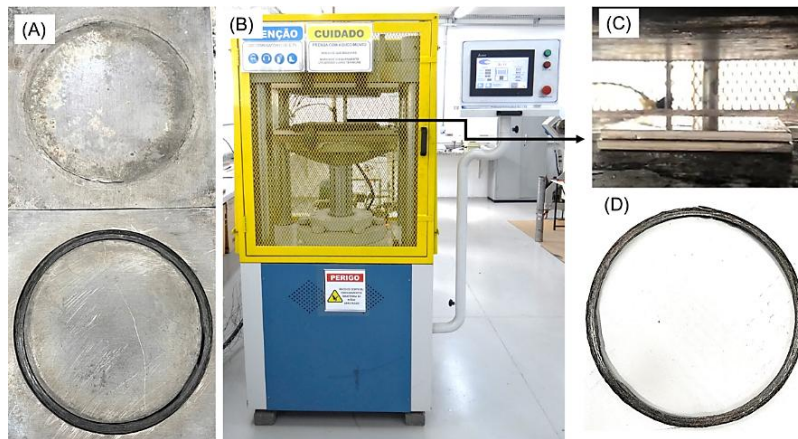


Fig. 4 - Compression molding of the CRO' inner composite reinforcement. (A) Metallic mold, (B) hydraulic press, (C) detail of CRO inner reinforcement being compacted, and (D) CRO inner reinforcement.

Another CRO inner composite reinforcements were manufactured by Mark-Two Markforged® 3D-printer model (Figure 5), consisting of a polyamide-based Onyx® chopped carbon

fibers and glass fiber (CF/Onyx and GF/Onyx). The proposal is comparing the tensile properties of commingled materials and commercial 3D-printed reinforcements for CRO.

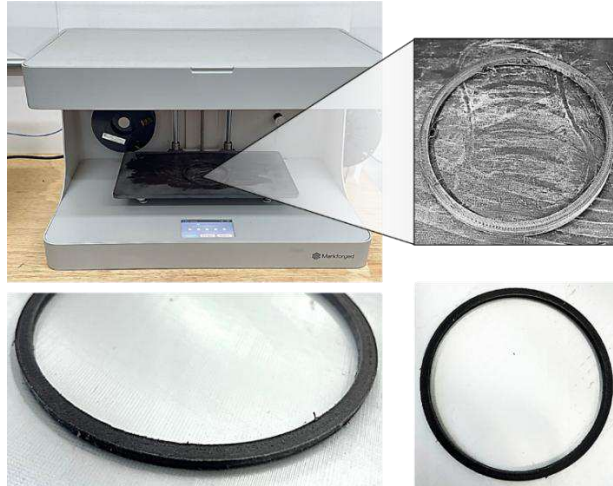


Fig. 5 - 3D-printed CRO' inner composite reinforcement using Markforged® printer.

To combine the CRO reinforcement with the elastomeric covering, a two-part mold was printed using polylactic acid (PLA) by Crealty Ender 5 Plus 3D printer. The CRO were coated by Dowsil™ 732 acetoxycure silicone supplied by DOW, which is a one-component material attractive for aerospace applications due to the temperature resistance, flexibility, proper adhesion to multiple substrates, durability and widely recognized to military specification for silicone sealants according to MIL-A-46106 ⁴¹. The Dowsil™ 732 technical datasheet indicates that the silicon remains stable and flexible from -60°C to 180°C, and has a tensile strength of 2.3 MPa ⁴². The CRO were demolded after 24h of curing at room temperature. The manufacturing of the PLA 3D-printed mold and the final aspect of CRO are shown in Figure 6.

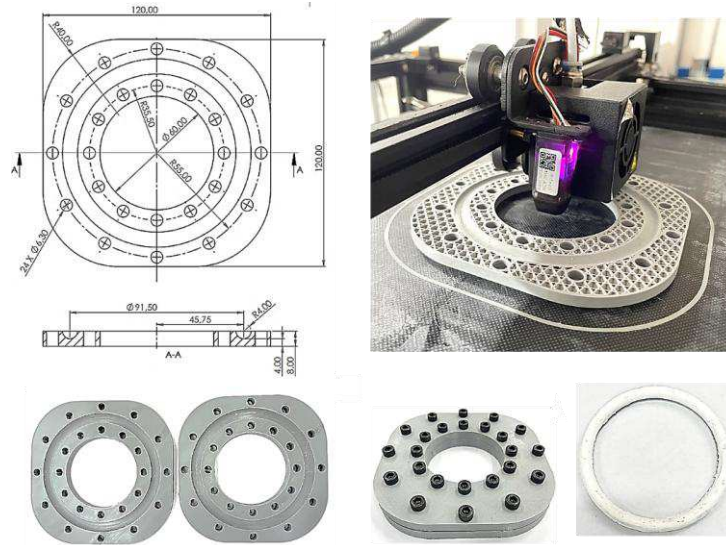


Fig. 6 - Design and fabrication of CRO 3D-printed mold revealing the CRO fabrication.

CRO Tensile testing was based on the procedures of ASTM D2290, with changes in the dimensions of the mechanical device. The test was conducted by Instron 8801 universal testing machine with digital image correlation (DIC) system, that measures full-field motion and strain on a material's surface by tracking unique patterns (speckle patterns) in digital images taken before and during loading. Figure 7 shows the mechanical device design and developed for the test, as well as the image of the CRO being tested. Three samples of each CRO were tested. Additionally, three samples of Dowsil™ 732 with no reinforcement were fabricated to evaluate the tensile properties.

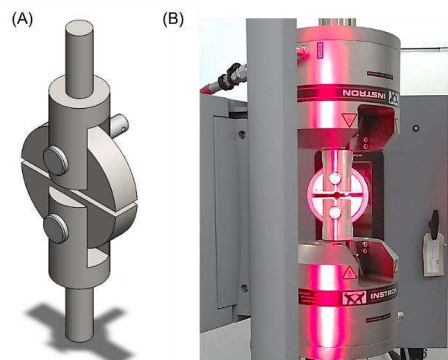


Fig. 7 - Mechanical device for performing the tensile testing on the CRO. (A) 3D illustration of the mechanical device, and (B) CRO being tested by an Instron 8801 with DIC system.

Tensile testing based on ASTM 3039 was applied to the composite materials in order to compare results with the CRO. CF/PEEK and GF/PEEK were fabricated using the filament winding followed by compression molding. The processing apparatus and processing parameters were based on previous study by Di Benedetto *et al.* (2022)^{13,36}. The samples of CF/Onyx and GF/Onyx composites were printed by Markforged® using the manufacturing standard parameters for each material. Three samples of each composite panel were submitted to tensile testing.

4. RESULTS AND DISCUSSION

Physical characterization through SEM and optical miCROcopy revealed the diameters of the reinforcement fibers and polymer yarns. Figure 8 shows the micrographs obtained for the commingled GF/PA and CF/PEEK tows, respectively.

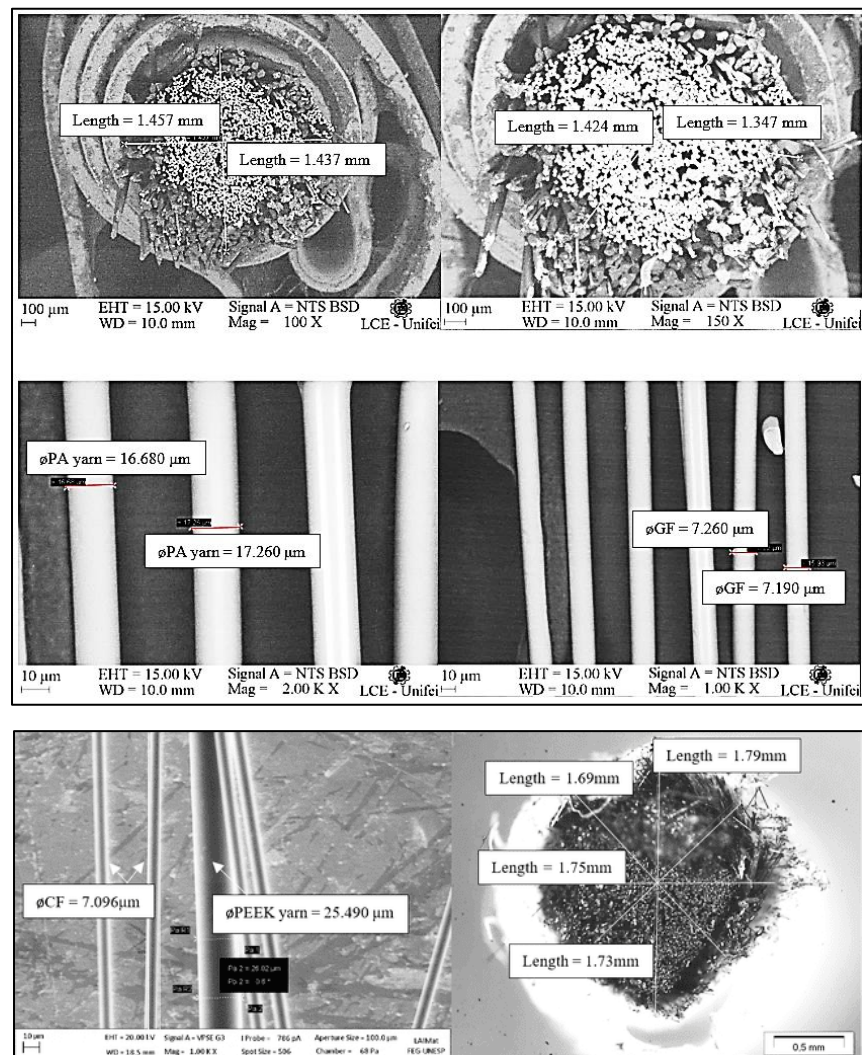


Fig. 8 – GF/PA and CF/PEEK commingled tow measurements.

GF/PA commingled tow presented a mean diameter and CROs-sectional area of 1.42 mm and 4.45 mm², respectively, while CF/PEEK showed values of 1.74 mm and 5.57 mm². GF/PA contains 55.55% glass fiber (with an average tow density of 1.90 g/cm³), while CF/PEEK consists of 47.37% carbon fiber (with an average tow density of 1.62 g/cm³).

The DSC analysis can reveal the main thermal phenomena occurred during a heating and cooling process. Thus, it guides the selection temperatures during the processing cycle of CF/PA commingled composite. Figure 9 shows the result obtained by the DSC analysis.

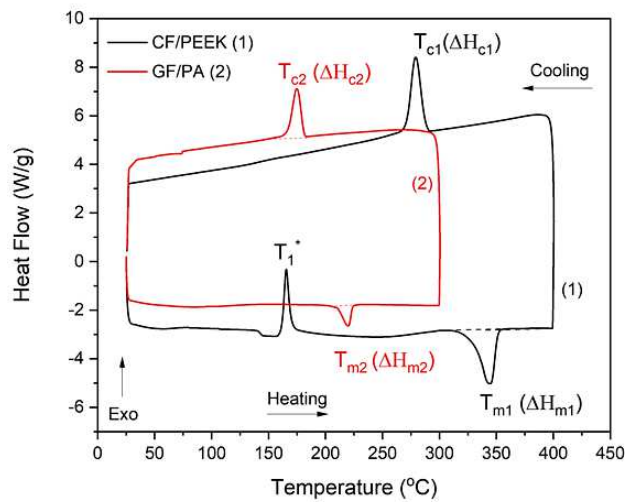


Fig. 9 - DSC heating and cooling thermograms of CF/PEEK and GF/PA commingled materials.

As shown in Figure 9, PA and PEEK are thermoplastic materials and presents the melting point (T_m), melting enthalpy (H_m), crystallization temperature (T_c) and crystallization enthalpy (H_c) for each commingled tow. An anomaly peak T_1^* was observed during the heating ramp of CF/PEEK. This peak refers to an apparent 'melting' at the glass transition temperature, and their cause is associated with stresses built into the material as a result of processing, handling, or thermal history, which are released when the material is heated through its glass transition⁴³. Due to the yarn manufacturing process, the polymer macromolecules exhibit a preferential orientation in the extrusion direction, resulting in an aligned molecular arrangement. This phenomenon occurs at T_g because of the molecules transition from a rigid to a flexible structure, allowing them to move and relieve the stress. It causes effects on DSC results regarding molecular relaxation that usually

appears as a weak endothermic transition near the end of a glass transition. Note that PEEK presented T_1^* , while PA yarn does not. It occurs due to stronger intermolecular bonds of PEEK macromolecules. Table 2 shows the DSC results.

Tab. 2 - DSC results for GF/PA and CF/PEEK commingled tows.

Sample	T_1^* (°C)	T_m (°C)	H_m (J/g)	T_c (°C)	H_c (J/g)
GF/PA	-	220	18.8	175	22.6
CF/PEEK	165	345	37.5	279	37.6

Through DSC analysis, the processing temperatures for the materials were identified, which must be above the melting temperature (T_m) but not exceed the degradation limits determined by TGA .

After evaluating the DSC results, the processing parameters for consolidating the materials were defined, adhering to the time and temperature limits for thermal degradation. The thermal processing cycle consists of a heating ramp (5°C/min) followed by a soak time (isothermal), as previously defined by Darcy's law.

Sample	Processing Temperature (°C)	Soak time (min)	Pressure (MPa)	Pressure (t/m ²)
GF/PA	260	20	0.3	30
CF/PEEK	400	18	0.3	30

The definition of the processing parameters for the continuous commingled filament was defined according to the results obtained from the thermal analyses. However, it was necessary to define the combination of processing feed rate and temperature at which the filament would exhibit low porosity values, which is expected for an aeronautical component. A constant feed rate of 0.08 m/s was established to achieve high productivity. The porosity of the composite filament was measured as a function of the heating system temperature, as shown in Figure 10.

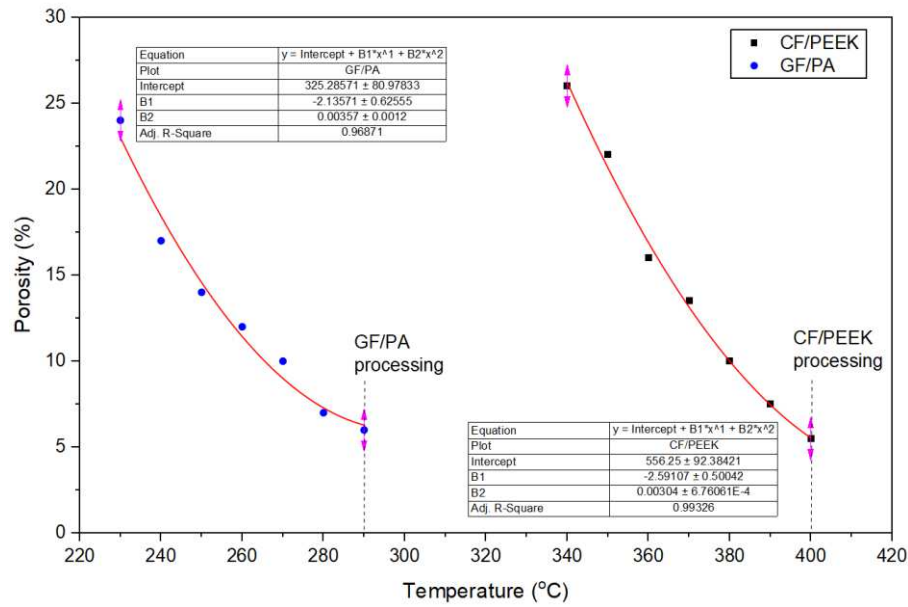
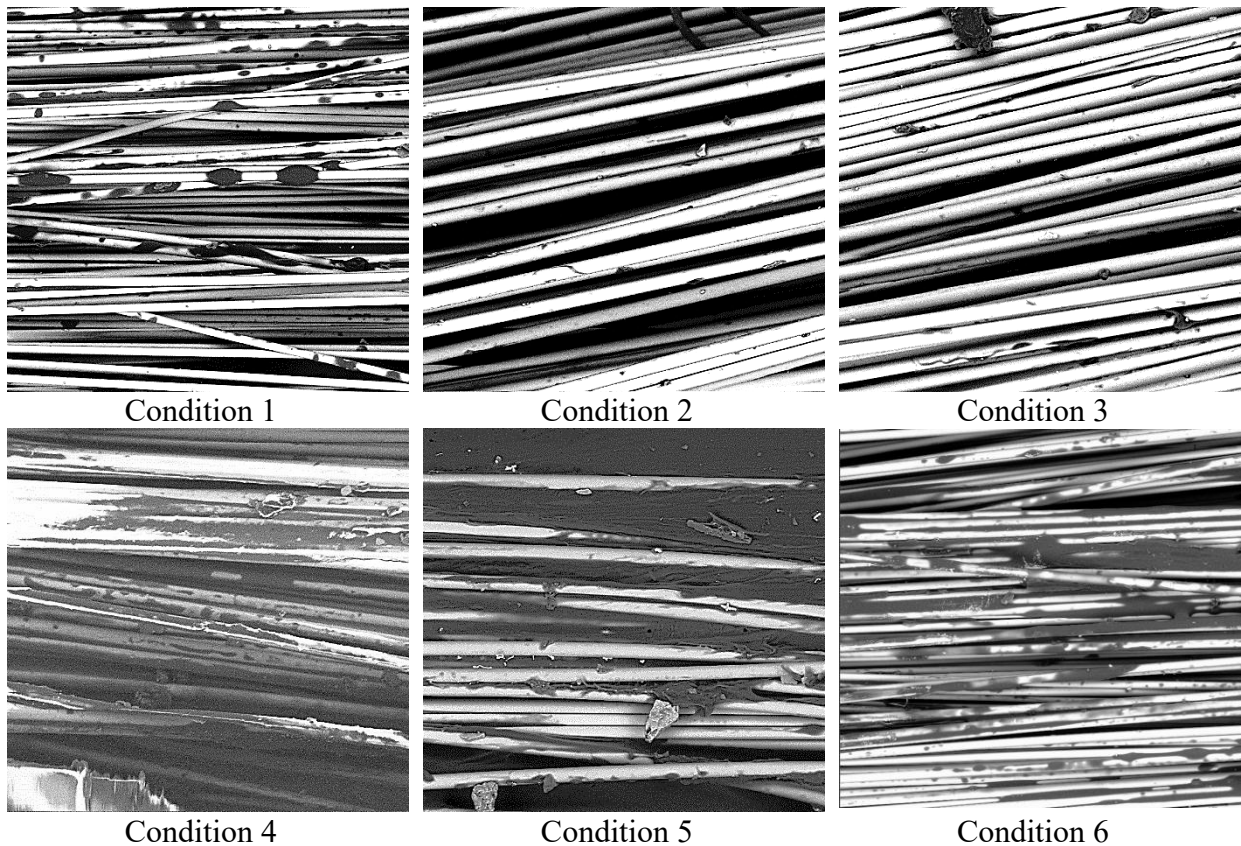
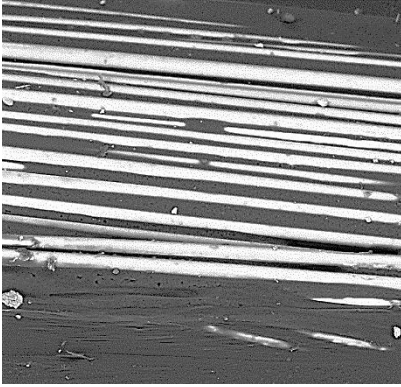


Fig. 10 - Commingled filament porosity in different processing temperatures.

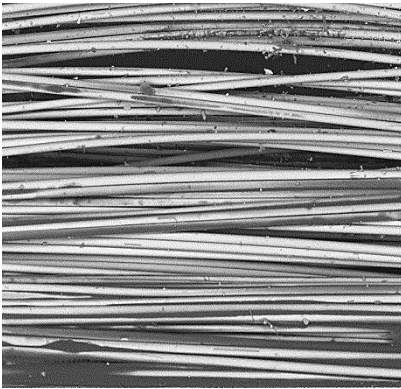
Figures 11 and 12 present the SEM micrography for each condition of processing used for CF/PEEK and GF/PA filaments, respectively.



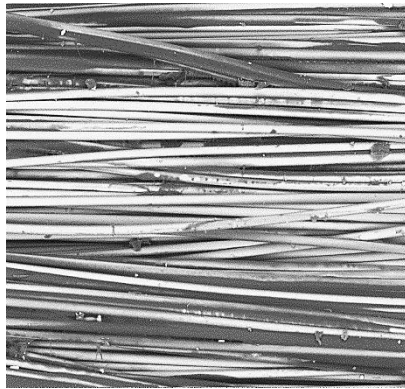


Condition 7

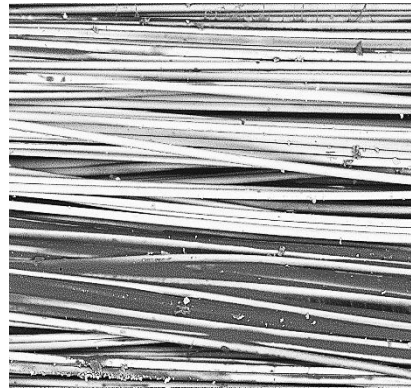
Fig. 11 - SEM miCROcopy of CF/PEEK commingled tow after being subjected to the processing conditions.



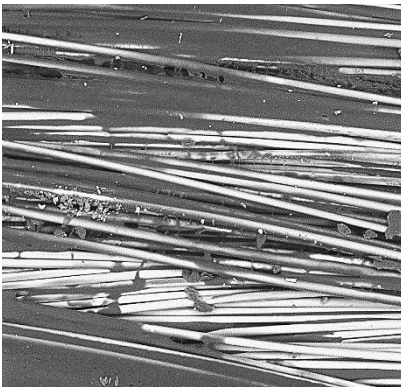
Condition 1



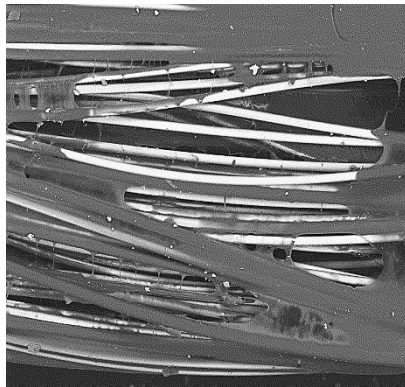
Condition 2



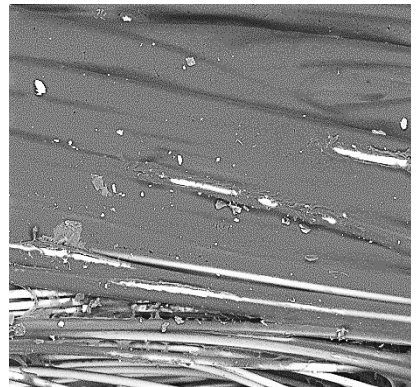
Condition 3



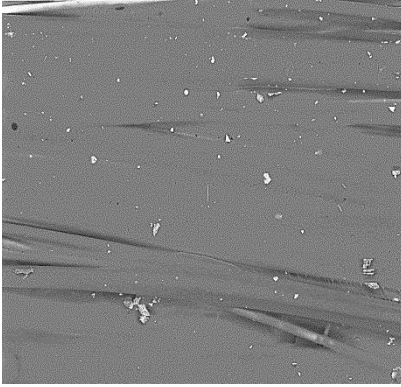
Condition 4



Condition 5



Condition 6



Condition 7

Fig. 12 - SEM miCROcopy of GF/PA commingled tow after being subjected to the processing conditions.

Although the tensioning system is not capable of totally consolidating the material, it was observed that polymer melting occurred in areas with higher matrix concentration. This strengthens the importance of guarantee the homogeneous fiber distribution profile to commingled tows. Consequently, the heating tensioning system was able to create a more compact pre-consolidated commingled continuous filament with lower internal void content as the temperature was increased.

The machine head developed for filament winding process operated consistently when the appropriate processing parameters were identified after several trials, including temperature, linear feed rate (deposition), and the heated rollers dimensions presented in Table 1. The best preconsolidation results, characterized by the absence of delamination in the wound layers during the filament winding process, were achieved at a temperature of 400°C for CF/PEEK and 260°C for GF/PA, considering the distances $R2 = 4.35\text{mm}$, $L2 = 8.10\text{mm}$ and $D2 = 11.90\text{mm}$. The contact heat area refers to the percentage of contact between the commingled tows and the inner cylindrical rotated system, and it is directly associated with the values of $R2$, $L2$ and $D2$. Using these parameters, the commingled filaments presented a mean of width and height of 3.7 mm and 0.35 mm, respectively.

The Markforged® 3D printer was able to produce inner composite reinforcements with high dimensional precision. However, due to the printer system, the reinforcement fibers are deposited only in some section, preferably at the external faces of the inner reinforcement rings. The processing time is higher than the commingles ones, although it requires less manual labor.

The results of the tensile tests are represented in Figure 13. The specimen length was considered the distance between the upper and lower fasteners from the mechanical device developed, therefore $l_0 = 4\text{mm}$. At the beginning of the test, the fasteners compressed the elastomeric part of the CRO, which directly influences the product's behavior. After this compression period, the tension of the free part begins to act significantly, and therefore was considered in the characterization. Also, the sampling axial area was considered multiplied by two, since the O-rings have two sections submitted to the tensile requesting effort.

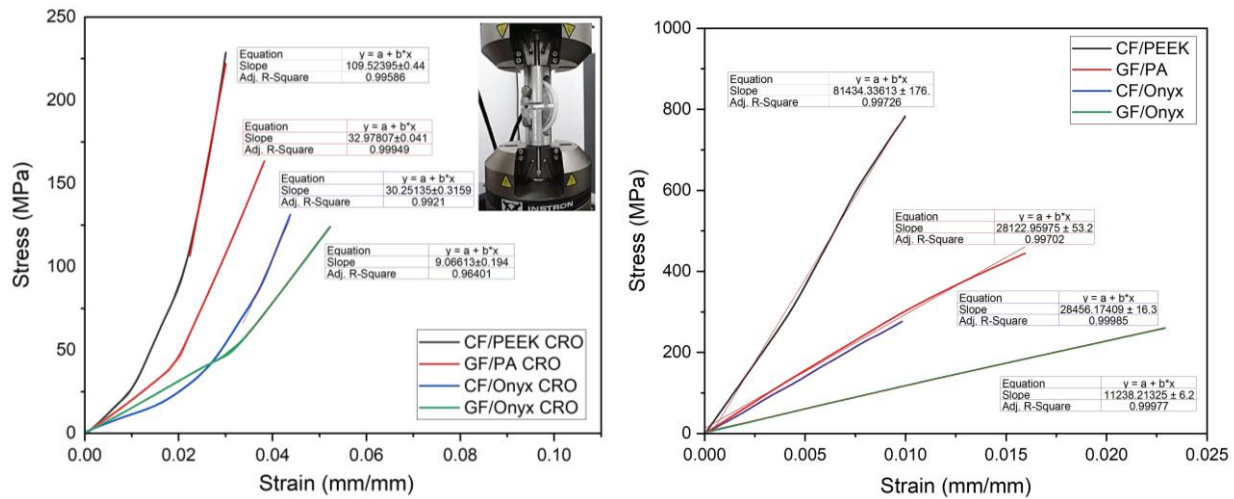


Fig. 13 - Mean of CRO and composite panels tensile test results.

According to the Figure 13, it is possible to clearly recognize the effect of compression of the elastomeric coat at the beginning of the tensile tests, what was disregarded in the characterization of the CRO. CF/PEEK CRO exhibited superior tensile properties, including a mean of elasticity modulus (E) of 109 GPa and tensile strength of 228 MPa. GF/PA and CF/Onyx CRO showed a close mean of E , 32 and 30 GPa respectively. GF/PA CRO presented a mean of tensile strength equal to 163 MPa. Finally, GF/Onyx showed 9 GPa of E , and tensile strength of 124 MPa. The O-ring made of Dowsil[™] 732 with no inner reinforcement presented mean of E equal to 0.5 GPa, mean of tensile strength equal to 1 MPa, and mean of strain equal to 170 %.

The tensile properties of the composite materials exhibited a tensile profile consistent with the CRO, although the average strength values were higher, due to the linear alignment of the reinforcing fibers. Table 3 shows the comparison between the tensile properties of commingled and Markforged[®] panels and CRO.

Tab. 3 - Tensile properties of composite panels and CRO.

Mean of Property		Tensile Strength (MPa)	Tensile Strain (%)	Elasticity Modulus (GPa)
Commingled composite	CF/PEEK	786.33	0.01	81.43
	GF/PA	444.74	0.02	28.12
Markforged composites	CF/Onyx	278.20	0.01	28.46
	GF/Onyx	261.99	0.02	11.23
Commingled CRO	CF/PEEK	228.79	0.03	109.52
	GF/PA	163.58	0.04	32.97
Markforged CRO	CF/Onyx	131.45	0.04	30.25
	GF/Onyx	123.99	0.05	9.06

5. CONCLUSION

This study demonstrated the feasibility and effectiveness of reinforcing elastomeric O-rings with high-performance composite materials to overcome the limitations of conventional sealing solutions in aeronautical systems. The incorporation of continuous fiber-reinforced thermoplastic composites, specifically referring to carbon fiber/PEEK and fiberglass/PA commingled technology in O-rings, proved to be a reliable technology that withstands demanding mechanical conditions, thus increasing the reliability of these components.

The machine head developed for use in the filament winding process has proven effective in the preconsolidation of commingled tows. Another advantage is the possibility to adapt the machine head to 3D printers. Preliminary tests indicated that pre-consolidation depends directly on the contact area of the commingled tow with the heated rolls. Values below 50% were not able to transfer sufficient heat for a suitable pre-consolidation quality. Temperature and feed rate are parameters determined according to the quality of pre-consolidation, which affects the interfacial adhesion between the deposited layers of the hoop-wound reinforcement, and it must avoid the polymer thermal degradation. Although it is an easily applicable technique, it still depends on a subsequent compression molding process to achieve the compaction quality of aeronautical products.

3D-printed continuous fiber composites are an innovative solution for aeronautical components. They represent an easy-to-handle technique capable of producing high-strength and dimensionally precise products. However, the manufacturing time is still long compared to the manufacturing time of filament winding technique with the machine head developed in this study.

6. ACKNOWLEDGMENTS

The authors acknowledge the financial support from National Council for Scientific and Technological Development (CNPq) under project 407431/2022-5, 447331/2024-8 and 303160/2023-3; from Research Foundation of the State of Minas Gerais (FAPEMIG) under project APQ 01846-18, APQ 00853-25 and APQ 07473-25. The authors thank the Composite Technology Center (NTC) from the Federal University de Itajubá-Brazil for the general facilities.

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