Low-cost Manufacturing Tooling for Titanium-CFRP Interfaces with Applications in Launch Vehicle Interstages

Mateusz Lentner[(1)], Marcel Kwapień[(2)], Nachiket Dighe[(3)], Gonçalo Fernańdez-Nespral[(4)]
[(1)] *Ceres Space B.V., Kapteynstraat 1, 2201BB, Noordwijk, The Netherlands,*
Email: mateusz@ceres-space.com
[(2)] *Delft Aerospace Rocket Engineering, Mekelweg 4, 2628CD, Delft, The Netherlands,*
Email: M.T.Kwapien@student.tudelft.nl
[(3)] *Delft Aerospace Rocket Engineering, Mekelweg 4, 2628CD, Delft, The Netherlands,*
Email: N.P.Dighe@student.tudelft.nl
[(4)] *Delft Aerospace Rocket Engineering, Mekelweg 4, 2628CD, Delft, The Netherlands,*
Email: G.FernandezNespralVaz-1@student.tudelft.nl

Abstract

Composite structures represent state-of-the-art lightweight design solutions for aerospace systems, particularly spacecraft and launch vehicles. However, these materials present challenges when joined with fasteners that require drilling. While adhesive joints are typically preferred for this application, they do not allow for disassembly after binding. Hybrid metal-composite interfaces solve this challenge by providing the mechanical functionality of metals while retaining the lightweight characteristics of composite structures.

This paper presents a low-cost method for manufacturing low-tolerance titanium-CFRP joints for cylindrical sections of sounding rockets. The design combines a titanium conical radax joint with a pre-preg carbon-fiber epoxy resin weave. An aluminum mandrel, lathed with a 0.1 mm tolerance, serves as the primary tooling, by maintaining concentricity and alignment. The total tooling cost was €324. A sanding precision of 50 µm of the composite cylinder is achieved using a rotary dremel mounted on an X-Y linear table. Secondary bonding with epoxy adhesive connects the composite cylinder to the metal parts. Additional prepreg layers cover the joint before autoclave curing.

Introduction

Lightweight, additively manufactured titanium interface structures joint with precisely manufactured composite parts can create a robust, seamless connection for a hybrid metal-composite interface. With the application of affordable production techniques, the tooling cost of creating such joints is reduced to be accessible with the budget of student rocketry teams, while retaining a high quality of manufacturing. Composite structures represent the state-of-the-art in lightweight design solutions for aerospace systems, particularly for spacecraft and launch vehicles. Despite their optimised structural performance, these materials pose unique challenges in design and manufacturing. One of the most significant challenges is joining composites with other materials or structures. Conventional metal structures often rely on fasteners, but those requiring drilling or cutting through continuous fibers can significantly degrade the structural integrity of composites. Consequently, adhesive joints are preferred for these applications. However, purely adhesive joints do not permit disassembly after bonding.

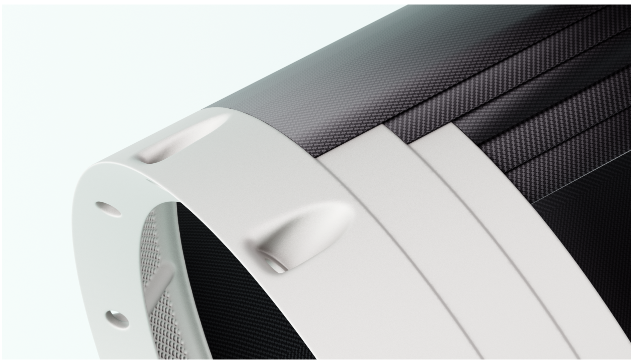


Figure 1. Schematic of the visible laminate plies flush with the titanium steps

Hybrid metal-composite interfaces (Figure 1, Figure 2) address this challenge by allowing metal components to provide mechanical functionality while preserving the lightweight characteristics of composite structures. In such interfaces, adhesive bonding is essential on the contact surfaces of both the metal and composite parts. Simple adhesive joint designs, such as butt and single lap joints, often result in high shear stresses towards the free edge of the joint. To minimise these peeling stresses, a double scarf joint (Figure 3) with a stepped profile, was chosen. This design ensures efficient load transfer through the hybrid interface but demands low tolerances during manufacturing.

Figure 2. Photograph of the final manufactured product

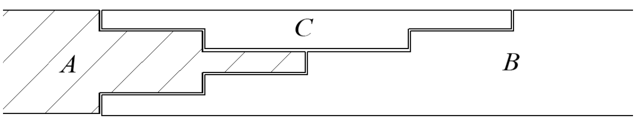


Figure 3. Interface schematic section view. Labels A, B, and C correspond to the metal ring, composite tube and composite interior scarf, respectively.

This paper proposes a low-cost method for manufacturing a low-tolerance titanium-CFRP joint for single-curved shells. The application focuses on cylindrical sections of sounding rockets, such as interstages, as this technique was developed as part of the DODO rocketry project by Delft Aerospace Rocket Engineering [1]. The DODO project aimed to compete in the European Rocketry Challenge [2] in the 9 km apogee category, utilising a student-researched and developed bipropellant liquid rocket engine fueled by ethanol and hydrogen peroxide.

[1]https://dare.tudelft.nl
[2]https://euroc.pt

The design integrates an additive manufactured conical radax joint made from Ti-6Al-4V alloy with a pre-preg carbon-fiber epoxy resin weave. This combination leverages the benefits of lightweight additive manufacturing and carbon composites, creating a solution that enhances the performance of both materials.

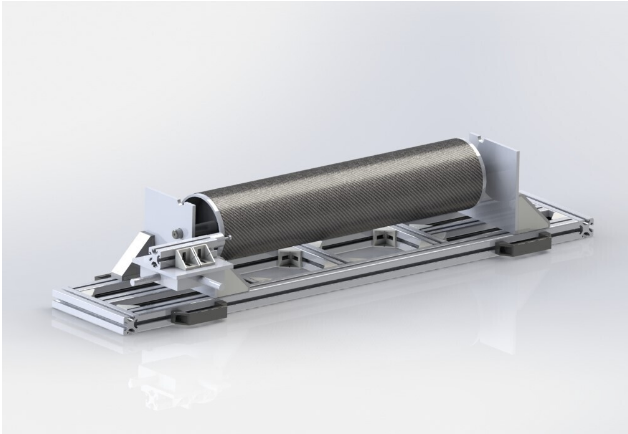


Figure 4. Tooling: An Aluminum Mandrel for lay-up and sanding operations

Fabrication of the joint required precise tooling. The primary tool used was a multi-purpose mandrel, depicted in Figure 4. This mandrel consists of a one-meter-long 6060-T66 aluminum tube machined to a maximum tolerance of 0.1 mm in outer diameter, constrained by the stock material characteristics. To maintain alignment between the mandrel and the additive manufactured titanium joints, a common datum was used throughout the machining process of both parts. This datum was subsequently transferred to the composite shell, with the mandrel being used for the hand lay-up of uncured composite plies, sanding of the cured composite cylinder, and top scarf layup.

Precise sanding of the composite cylinder's steps was critical to meet the low-tolerance requirements of the additive manufactured components. To achieve this, the mandrel was equipped with a rotary Dremel mounted on a manual X-Y linear table, capable of delivering a precision of up to 50 µm. This setup ensured that the datum was maintained throughout the manufacturing process for both the composite and metal parts.

Secondary bonding was achieved using a spread-form of two-part epoxy thixotropic adhesive to connect the composite cylinder to the metal parts. As shown in Figure 3, this adhesive bonds part A to part B to create the interior scarf of the joint. The bondline thickness was controlled by mixing microballoons (ranging from 1 to 50 micrometers in diameter) into the adhesive paste to correct for any misfit, a common issue when joining two stiff substrates. The co-bonded joint was then covered with the remaining layers of prepreg (indicated by the letter C) and cured in an autoclave.

This paper not only details the procedure used and the materials employed but also presents an analysis of the manufactured shells, demonstrating the precision achieved by this method and its potential applications in advanced aerospace systems.

Materials & Processing

Composite prepregs and Adhesives

The shell material consisted of Carbon Fiber Reinforced Plastic (CFRP) pre-impregnated with a temperature-curable resin. Due to budget constraints and material availability, experiments were conducted using three different commercially available prepregs from two manufacturers: Gurit and Solvay.

Gurit's woven SE 75-T1 RC High-Performance Prepreg System[3] was utilised in two areal weights—200 gsm and 416 gsm. This pre-preg was cured at 70°C for 12h. Additionally, Solvay's MTM® 45-1 high-performance epoxy matrix prepreg,[7] available in an 8HS fabric form, was employed. A cure cycle with a dwell temperature of 80°C for 20h was selected. Both prepreg systems offer suitable out-of-autoclave properties for the intended interstage application.

For testing purposes, various adhesive forms were evaluated. Initial samples were fabricated using an adhesive film; however, significant wrinkling during the assembly process necessitated a switch to an alternative paste adhesive. The final adhesive selected was Araldite® 2015-1,[4] a two-component epoxy paste chosen for its availability and high bond strength. Although sufficient bond strength for handling was achieved, curing was required.

For future applications, an evaluation was conducted using VM100 Black MMA Structural Acrylic Adhesive.[1] Unlike the epoxy adhesive, VM100 offers the advantage of room temperature curing, eliminating the need for an oven. This made the process more convenient and significantly faster, presenting a promising alternative for situations where time efficiency is critical.

Lay-up Procedure

The mandrel was removed from the tool and coated with a release agent (Marbocote HP7[6]) at least three times to ensure adequate coverage. Concurrently, the first three layers of the pre-preg were cut to precise lengths, maintaining an observed tolerance of less than 2 mm to ensure flush edges. Each layer was then laid up with their meeting edges offset by 60 degrees to minimise the accumulation of fiber discontinuities. The prepared CFRP shell was first wrapped with peel ply, low-perforated release film, and breather material before being vacuum-packed to a pressure of at least 900 mbar. The shell was then cured in an autoclave at 4 bars, with the cure cycle tailored to the specific prepreg used. After curing, the composite cylinder was repositioned on the mandrel, and the composite steps were carefully sanded using a rotary Dremel tool attached to an additional mandrel arm to achieve the required ring diameter. Due to the inherent limitations in printing and machining, the diameters of the composite steps were adjusted to fit the titanium interface. The steps were subsequently treated with isopropanol solvent and sanded to increase surface roughness, thereby enhancing adhesion.[8] Adhesive material premixed with microballoons was applied to the interface ring, which was then placed onto the shell's steps at both ends. Depending on the adhesive used, the assembly (shell with rings) was either left at room temperature or cured in an oven to achieve initial bond strength. To ensure the highest tolerance between the ring steps and the remaining CFRP layers, the widths were measured after ring adhesion. The remaining CFRP layers were then laid up on top of the titanium rings. The entire assembly was once again wrapped, vacuum-packed, and cured. Post-processing involved sanding any ridges and creases caused by the vacuum-packing process, followed by the application of a clear coat to protect the top layer of fibers.

Tooling

Appropriate tooling is required to fabricate the joint connection between the composite shell and the titanium ring. For this purpose, a multi-purpose mandrel has been created, as shown in Figure 4. It allowed for the pre-preg layup, sanding operations and alignment operations. The entire setup consists of multiple elements as presented in the Figure 5 and explained in the Table 1. The most important element to achieve the necessary tolerances is the aluminium mandrel. To create the tooling, the one-meter-long 6060-T66 aluminium tube was firstly internally welded to create the bulkheads, as attachment points. Then the entire outer surface was lathed down with a maximum machining tolerance of 0.1 mm, limited by the stock material characteristics. A significant amounr of material was removed as the initial aluminium tube did not have the required concentricity.

However, to keep the rocket concentricity aligned across its entire length, the datum point for the machining was created. All the parts, including the mandrel were machined according to this datum. Thanks to this approach, the alignment of the additively manufactured titanium joints with the carbon shell could be performed. The transfer of the datum point for the mandrel and consequently carbon was done through the dead centres as presented in the Figure 5.

Once the mandrel was machined to the required outer diameter, it was placed between two dead centers and locked on the mounting structure made out of the aluminium extrusion elements. The side supports and the bulkheads inside the mandrel have conical holes to keep the dead centres in place. This type of structure was used as it heavily minimised the costs as presented in the Table 2. All the used elements could be easily purchased from the local suppliers and the modular design allowed for the adjustments in case smaller parts had to be aligned.

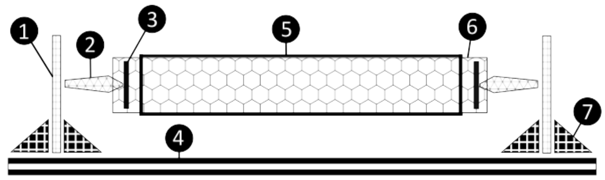


Figure 5. Mandrel schematics

Table 1. Bill of materials of the tooling setup

Number	Element of the tooling
1	Aluminium plate - side support
2	Lathe dead centre
3	Mandrel bulkhead
4	Aluminium extrusion supporting structure
5	Composite layup
6	Aluminium mandrel
7	Brackets

Table 2. Cost budget of the tooling setup

Element	Cost [€]
Aluminium extrusions	76
Joining elements	78
Bulkheads	34
Supporting plates	36
Mandrel	100
Machining	in-house
Total:	324

Lastly, the tooling also had a dremel attachment point placed on the X-Y linear table, not present on the graphical schematics. This way the precise sanding of the steps feature on the composite shell could be done. The linear table together with the free rotation of the mandrel allowed for the sanding operations of up to 50 µm. This precision was required to keep the steps consistent across the different parts and with respect to the additively manufactured rings.

Results

To quantify the achieved geometric tolerances after manufacturing and sanding, a manual vernier caliper was used to measure various dimensions. The vernier caliper has a measurement accuracy of 0.02 mm. Figure 6 depicts typical dimensions of the stepped carbon ring that can directly accessed by the calipers.

Concentricity

Utmost care was taken during the machining of the mandrel to maintain maximum concentricity of the tooling setup. Unfortunately, several factors contribute to the slight ovalisation of the carbon tube. During machining, for example, a dead centre can only dampen the rotational vibrations but cannot completely eliminate them. In addition, the mismatch of thermal expansion coefficient between aluminum and carbon causes the plies to contract more during autoclave curing. Ovalisation may further have been amplified during demoulding of the carbon ring. This could especially be caused by the welded aluminum bulkheads (necessary for mounting the mandrel on the lathe) over-expanding during heating and enlarging the cross-section towards the end of the mandrel.

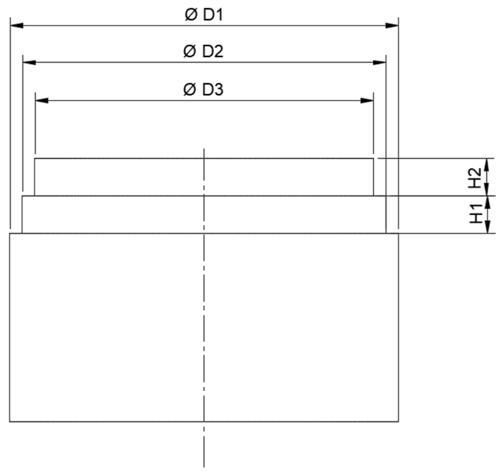


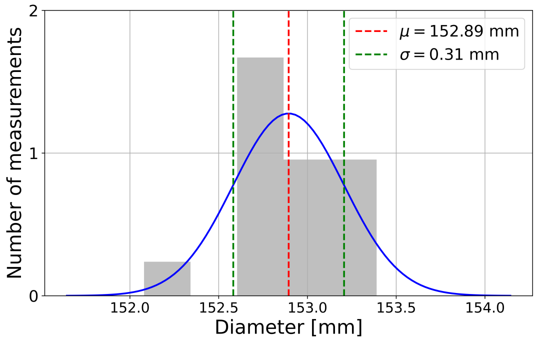
Figure 6. Carbon ring schematic with step feature (not to scale)

To gain insight into the degree of ovalisation, the diameter was measured across various points on the carbon ring's cross section. Figure 7 presents the diameter measurements for a single stepped carbon ring, corresponding to the schematic shown in Figure 6.

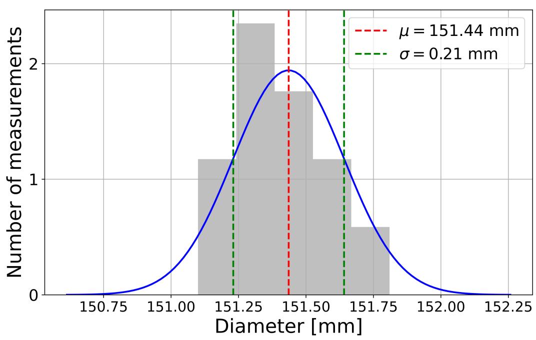
The standard deviation of the diameter measurements are of interest. It physically signifies the variation of local cross-section length with respect to a perfect circle of a mean diameter μ. D_1 has the maximum standard deviation of 0.33 mm, whereas D_3 has the minimum of 0.33 mm. This means that the ovalisation effect increases with the outward radial distance. It is most pronounced for outer plies.

As such, more measurements were performed on the outer diameter D_1 of the manufactured rings, with the results visualised in Figure 8. Unfortunately, at the time of measurement, rings 1-4 were already adhesively bonded. That means that it was not possible to measure the diameter at every step of the joint.

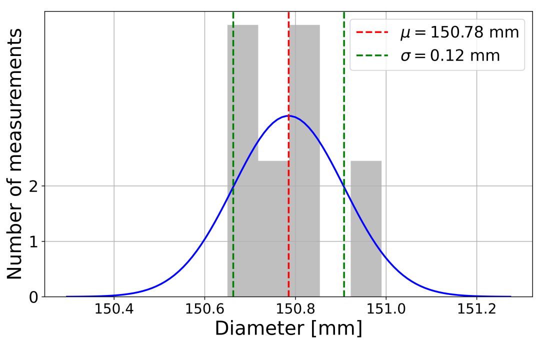
Based on Figure 7-8, the range of cross-section length is less than 1.5 mm, for a nominal diameter of order of magnitude of 150 mm. Neglecting caliper measurement error and conservatively considering the surface to be smooth (free of bumps or creases), less than 1% ovalisation is achieved on the carbon tubes.



(a) D_1 (outermost)

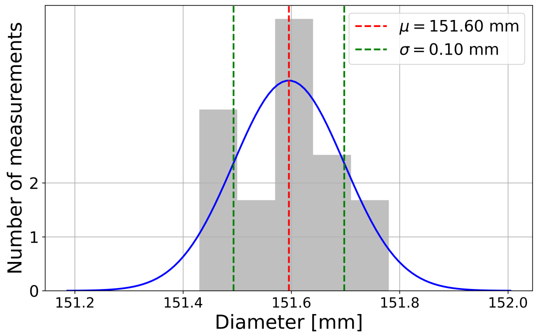


(b) D_2

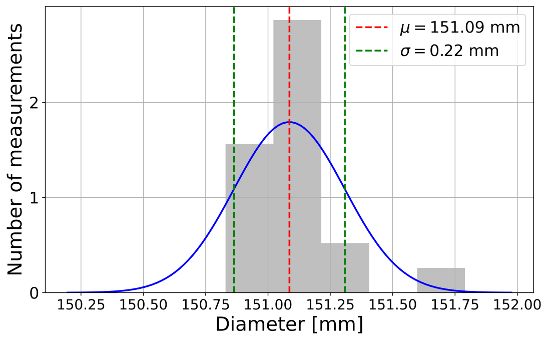


(c) D_3 (innermost)

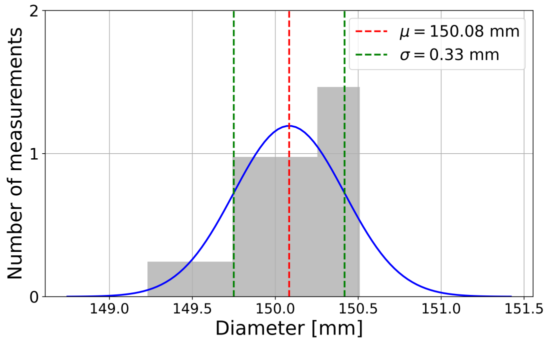
Figure 7. Normally distributed measurements of a single stepped carbon ring's diameter



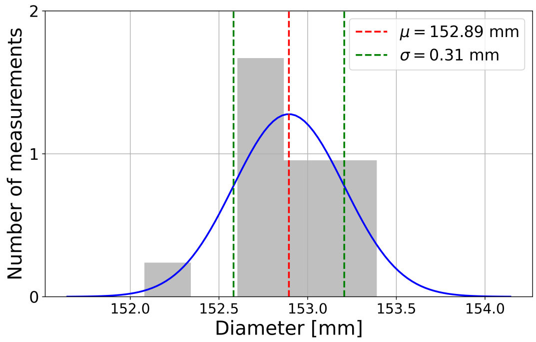
(a) Ring 1



(b) Ring 2



(c) Ring 3



(d) Ring 4

Figure 8. Normally distributed measurements of multiple carbon rings' outer diameter

Step Thickness

The total thickness of a composite structure is typically kept as an integer multiple of the cured ply thickness. However, this is not possible in a hybrid metal interface, where the titanium is additively manufactured. The geometry of the metal ring is constrained by the layer height of the printer. In Direct Metal Laser Sintering (DMLS), dimension accuracy of ±0.3 mm and layer height in the range of 40 µm to 80 µm is expected.[5] Consequently, the steps of the carbon ring have to be oversised in the thickness direction and sanded down to become flush with the titanium piece.

A loose fit on the metal-composite interface could be catastrophic on the structural performance of an launch vehicle intertank stage. Premature joint failure may occur in tensile loading, if the gap between the metal and composite exceeds the gap-fill distance of the adhesive. Alternatively, tight interference fits may cause unexpected residual stresses that could potentially damage the thin step features or amplify unnecessary ovalisation.

Therefore, the thickness that needs to be sanded Δt_{sand} needs to be carefully pre-determined. Equation 1 is proposed to allow a seamless fit of the carbon ring with the titanium counterpart.

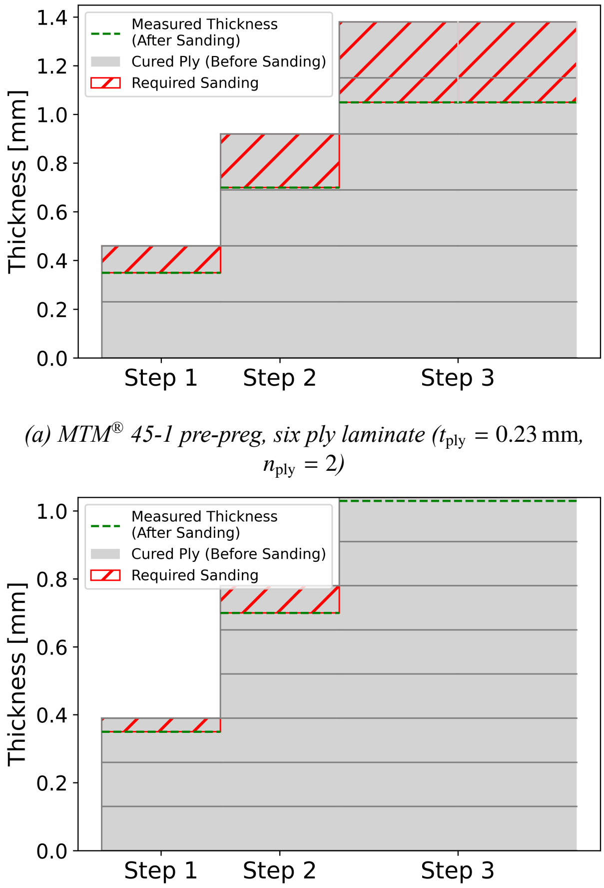
$$\Delta t_{\text{sand}} = n_{\text{ply}} \cdot t_{\text{ply}} - t_{\text{metal step}} + t_{\text{bondline}} \tag{1}$$

$t_{\text{metal step}}$ is the thickness of the step feature on the additive manufactured titanium ring. A default step thickness of 0.35 mm is taken from the CAD, as previous shown in Figure 1. To improve the estimate of step thickness, it is recommended to measure the titanium ring step thickness after its DMLS fabrication. In case of post-processing operations to remove support material, $t_{\text{metal step}}$ should be updated after the metal ring has been cleaned and post machined.

t_{bondline} accounts for the bondline thickness. If film adhesive is used, t_{bondline} can be taken as the cured film thickness specified in the manufacturer's technical datasheet. In case of paste adhesive mixed with microballoons, the bondline thickness can be approximated as the diameter of the microballoons. Typically, microballons are of order of magnitude of 50 µm for epoxy adhesive applications.[2]

n_{ply} refers to the number of plies needed in the step. n_{ply} depends on the cured ply thickness t_{ply}, that is different for pre-preg weaves with different areal weight and supplied from different manufacturers. Figure 9 illustrates the achieved sanding levels from two different pre-pregs.

The measured thickness of the step features in Figure 9 is taken as half the difference between the measured outer diameters (as schematically shown in Figure 6). It can be seen that the achieved step thickness exactly matches with the desired step thickness. A tolerance of at least 50 µm has to be allowed to account for the measurement uncertainty of the caliper.



(a) MTM® 45-1 pre-preg, six ply laminate (t_{ply} = 0.23 mm, n_{ply} = 2)

(b) SE75-T1 RC 200 gsm pre-preg, eight ply laminate (t_{ply} = 0.13 mm, n_{ply} = 3)

Figure 9. Desired (CAD) and achieved (measured) sanding thickness for cured stepped carbon ring ($t_{\text{metal step}}$ = 0.35 mm, t_{bondline} = 50 µm)

Nevertheless, the necessity for sanding in stepped hybrid metal interfaces can be illustrated by Figure 9a. A few tenths of a millimeter have to be adjusted to match the thickness of the carbon ring with that of the titanium one. This is especially prevalent for thicker pre-preg weaves- that are advantageous in terms of more robust handling, lower raw material cost and shorter layup time.

The sanding operation may be avoided if higher tolerances (order of magnitude of 0.1 mm to 0.2 mm) and variable bond-line thickness at the interface are acceptable. Trivially, the benefit of the sanding operation diminishes for thinner plys as a smaller amount of material needs to be removed. This is shown by Figure 9b, as it generally has smaller red hatched regions than Figure 9a.

Recommendations

The following recommendations aim to address the limitations encountered during the current study and suggest methods for improving the manufacturing process and performance of the titanium-CFRP interfaces in future iterations.

Firstly, it is recommended to conduct an extensive mechanical test campaign to determine the stiffness and strength of the stepped hybrid interfaces. The possibility of using the Universal Testing Machines (UTMs) at Delft Aerospace Structures and Materials laboratory was considered. However, due to the cylindrical nature of manufactured pieces, large custom-made clamps would be required to connect the specimen to the machine. Destructive testing would have been prohibitively expensive predominantly due to the high raw material cost and long processing time (printing and post-machining) of the titanium parts. Even if destructive lap-shear or tensile tests were conducted, the carbon shell was expected to fail first. No information on joint strength would have been extracted as the first failure mode was neither cohesive nor adhesive. Only by altering the geometry of the interfaces, it would have been possible to manipulate the sequence of failure modes. This did not add extra value in the context of project DODO, as the nominal diameter of the liquid bi-propellant rocket was constrained at an earlier design phase. Therefore, it is recommended to tensile test smaller specimen to verify adhesive bond strength and elastic modulus at the interface. Fatigue and impact testing are also recommended to determine performance under both cyclic and high-energy loading conditions, respectively.

Over and above that, the results presented in the paper are solely based on vernier caliper measurements performed before the carbon ring is adhesively bonded to the titanium ring. It is of interest to characterise the hybrid interface after it has been bonded, to investigate the effect of the adhesive curing cycle on the geometric tolerancing of the stepped joint. Only a non-destructive testing method would be able to measure bondline, carbon and titanium step thicknesses after adhesive curing. For example, through transmission of bulk ultrasound waves can be performed to obtain A-scans of the cross-section showed in Figure 3. However, such an inspection procedure may require cumbersome calibration, due to the curved shape of the structure representing the cylindrical interstage.

Following this, further research into suitable adhesives is recommended. More extensive work should be conducted to explore different types of adhesives and their performance (making use of the testing recommendations) in this specific application.

Initial experiments involved the use of glass microballoons with Araldite® 2015-1 to control the bondline thickness. However, the use of this requires more comprehensive testing. It is recommended to carry out a further investigation into the optimal ratio of microballoons to adhesive, as well as the impact they have on the bond strength and the consistency between parts. The former may be carried out by destructive testing, and the latter by the testing methods recommended previously.

The machining of titanium presents challenges that affect tolerancing. Even with substantial coolant use, thermal expansion occurs, impacting the precision of the machining process. Improved thermal management strategies should be investigated to maintain tight tolerances during the titanium machining process.

To ensure proper machining of the titanium rings, the use of an X-Y coordinate table is recommended. This would improve the precision and consistency of the step features, crucial for the fit and performance of the interface.

Conclusions

In summary, the proposed low-cost, precision tooling setup, centered around a multi-purpose aluminum mandrel, has proven sufficient in achieving the necessary tolerances for hybrid metal-composite joints in single-curved shells. The mandrel, machined to an outer diameter tolerance of 0.1 μm, effectively facilitated pre-preg layup, sanding, and alignment operations, ensuring concentricity and accurate fitment between the additively manufactured titanium interface rings and the composite cylinder. Despite challenges such as shell ovalisation, the setup maintained less than 1% deviation in concentricity, with diameter measurements showing a standard deviation below 0.33 μm for the outermost layers. Sanding operations achieved step thicknesses with a precision of ±50 μm, closely matching the desired values. This level of accuracy was particularly critical for ensuring a tight bond line thickness, typically maintained at around 50 μm, necessary for the structural integrity of the joint. The overall tooling cost was kept under €500, demonstrating the feasibility of this method for high-performance aerospace components, such as the interstage sections of sounding rockets. This approach not only ensures structural reliability but also provides a scalable solution for future applications in aerospace manufacturing.

Acknowledgements

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