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| PlasmaBound |
| DeRisk – Deliverable ESR |
| Executive Summary Report |

A close-up of a machine

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**Contract Number:** 4000134544/21/NL/GLC/va

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| Date: 26th June 2024 |

# Introduction

This document provides a synopsis of the De-Risk activity associated with Plasma Bound’s novel and patented CPA (Controlled Polymer Ablation) process. Illustrated on the title page is the CPA process treating the outside surface of a consolidated thin skinned sandwich panel.

## Purpose

This document aims to concisely summarise the findings of Plasma Bound’s Controlled Polymer Ablation (CPA) De-risk activity (Contract No. 4000134544/21/NL/GLC/va). It provides the rationale behind undertaking the activity (incl. the problem statement). In addition, the proposed and the potential impact its adoption may have on the space industry. Finally, potential follow-on activities are highlighted. This report forms a summary for the elevation of Plasma Bound’s CPA process to TRL 4, from TRL 2.

## Key Stakeholders

A list of key stakeholders in this activity include:

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| * Plasma Bound * European Space Agency * Enterprise Ireland * EireComposites * Composites Testing Lab | * Mbryonics * APCO Technologies * Mecano-ID * EuroComposites * Realtra |

This list of stakeholder companies includes ESA (European Space Agency), who requested the activity’s execution, and EI, who supported the activity proposal and Realtra a company who recently observed the potential benefits of Plasma Bound’s CPA technology beyond just secondary bonding.

# Objectives and Rationale

Detailed here are a summary of the objectives, and a reflection on some key achievements, with how these contribute to ESA’s overall mission and vision.

## TRL Elevation Objectives

The principal objective of the de-risk activity was to demonstrate CPA prepared CFRPs (Carbon Fibre Reinforced Polymer) materials can outperform the present SotA (State of the Art) prepared CFRPs in bond strength, quality, and reliability. Assessed from both a bond quality standpoint, but additionally, operational benefits (cleanroom or shelf-life) were assessed. The materials of interested where monolithic format (8 ply thick) and thin-skin format (4 ply thick) CFRP. Technology Readiness Level elevation from 2 to 4 was the target.

There were several key and peripheral objectives to achieve this elevation:

* Assess the present and future scope for potential hardware and process obsolescence from regulatory or supply chain impacts (TRL 3)
* Propose two space applications, one focused on monolithic and another on the thin-skin sandwich format, where Plasma Bound’s CPA technology will support Breadboard preparation (TRL 4)
* Develop and execute an element level Proof of Concept (PoC) plan to assess the viability of CPA to satisfy the chosen space applications (TRL 3)
* Develop and evaluate a suitable Breadboard model to satisfy a demonstration of CPA’s suitability to one or both space applications (TRL 4)

In summary, PlasmaBound’s De-Risk activity focuses on elevating Plasma Bound’s novel CPA process from TRL2 to attaining TRL4 status on two formats of CFRP material. Materials & Methods.

### State of the Art (Benchmark) – ‘The problem’

The present market standard, and SotA for monolithic and sandwich panels are mechanical abrasion and peel ply, respectively. These approaches were used to benchmark – but the difficulties around the material waste from consumables, consistency between preparations and contamination affect both methods. Putting significant financial, operation and commercial limitations on manufacturers and their adoption of CFRP materials.

#### Monolithic – Mechanical Abrasion

Many space operators use some iteration of the “abrasive surface preparation method” with a process flow of pre-clean, abrade (P240), post-clean, dry, and “immediately” bond. A significant drawback to hand abrasion is operator dependency, time dependency, labour intensity and dirty nature of the operation as well as, the environmental issues.

#### Sandwich Skins – Peel Ply

Involves the removal of the top of composite polymer through a 100% sacrificial fibre layer. This layer is immediately peeled prior to bonding, revealing a fresh surface of composite. A significant drawback to peel ply is residual contamination, release agent retention, and labour intensity, as well as the environmental issues (100% waste).

## Controlled Polymer Ablation

Plasma Bound’s novel and patented Controlled Polymer Ablation (CPA) process delivers controlled thermodynamic energy via an atmospheric plasma plume to the surface, destabilising the chemical bonds, causing a polymer vaporisation (or sublimation) event without damage to the composite’s structural efficiency.

In addition, CPA can remove any process fluids or handling oils which ordinarily require further cleaning steps. CPA acts as a single step solution – the prepared composite can go straight to bonding/joining or can be stored for bonding later. A brief illustration of the CPA’s effect on a woven fibre composite material is illustrated in Figure 2‑1. The original polymer surface and residual contaminants are removed in a single step, leaving the undamaged fibre structure which is ready to receive the adhesive. It is the inclusion of the fibre structure and ‘refreshing’ of the polymer structure that leads to the enhanced bond performance. The level of removal is fully tailorable, which means a single CPA cell can act for different applications, needs and even different polymer or fibre mixes.

A diagram of a structure

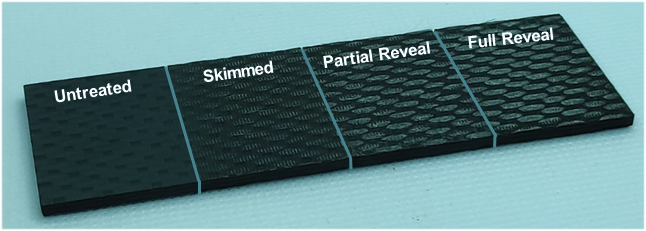
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Figure 2‑1: Left, illustrates the CPA process can treat both uncontaminated and surface contaminated polymer composite systems to reveal the fibre structure without a need for any cleaning steps, Right, the level of fibre reveal can be tailored (or optimised) for specific application needs, reveal more or less fibre depending on requirements and providing a tailored bond design.

# Impact and Benefits

## Increased Bond Performance and Confidence

Initially, a wide range of CPA treated groups were assessed using a range of mechanical tests and benchmarked against peel-ply. However, following this, a second FWT (Flatwise Tensile) campaign was undertaken with three ‘ideal’ CPA treated groups. The result of this round of testing demonstrated the clear distinction in performance between CPA and peel-ply prepared surfaces.

### Flatwise Tensile (FWT)

Flatwise tensile (FWT) testing was performed according to the requirements of ASTM C297-16. The test articles consisted of RS36 epoxy resin with M55J carbon fibre bonded with Loctite EA9695 epoxy film adhesive and machined to dimensions 50 × 50 mm. Ultrasonic C-scan NDT confirmed the specimen were suitable for testing. Three variants of CPA were prepared for comparison to the benchmark peel-ply surface - the 3 CPA variations are named Skim, Partial Reveal and Full Reveal, which refers to the amount of epoxy polymer removed from the surface by the CPA treatment. The test set-up is shown on the left of Figure 3‑1 and is suitable to determine the flatwise tensile strength of the core, the core-to-facing bond, or the facing of an assembled sandwich panel. The results are presented in box plot form on the right of Figure 3‑1. Compared to the benchmark peel ply prepared specimen, all CPA specimens measured higher FWT strength, lower standard deviation, and lower variance. Adhesive Failure of Core Facing Adhesive was the dominant failure mode across all groups. While a broad spread is observed in the Peel Ply data, the CPA groups recorded considerably tighter data spread. This is a common feature of CPA prepared surfaces.

Close-up of a machine

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Figure 3‑1: Left) Flatwise tensile tests were performed according to the requirements of ASTM C297-16. Right) Box plot presenting the FWT results for CPA Skim, Partial Reveal and Full Reveal and the benchmark, Peel Ply.

## Shelf-life Improvements

As before, a wide range of CPA treated groups were initially assessed using a range of mechanical tests and benchmarked against mechanical abrasion, however following this a round of FWT testing was undertaken with the ‘ideal’ CPA treated group – which focused on the storability of CPA prepared surfaces. Storage in these studies meant the prepared surfaces were left exposed to ambient conditions for extended periods before adhesive bonding occurred. The storage environment was Plasma Bound’s laboratory.

### Double Lap Shear (DLS) 168 hours storage

Double lap-shear (DLS) testing was performed according to the requirements of ASTM D3528-96 (2016). The test articles consisted of RS36 epoxy resin with M55J carbon fibre bonded with Loctite EA9394 epoxy paste adhesive. Ultrasonic C-scan NDT confirmed the specimen were suitable for testing. The goal of this test is to assess the effect of storage time on CPA performance at intervals of 0, 24, 72 and 168 hours (or 7 days) after treatment against the benchmark of mechanical abrasion which were bonded immediately after preparation.

The left of Figure 3‑2 illustrates the test setup, and the results of the CPA Partial Reveal storage time DLS tests with benchmark are on the right of Figure 3‑2. Across all groups, low standard deviation, low variance and high percentage of cohesive failure were measured.

Close-up of a machine

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Figure 3‑2: left) DLS Test Set Up. The test speed used was 1.27mm/min crosshead displacement and specimens were loaded until failure occurred. Right) Box plot presenting the DLS results for CPA Partial Reveal treated specimen after storage time (note: These results are presented in MPa, converted from kg/cm² which is the unit in accordance with the testing standard). The 0-hour value for a hand sanded group provides a benchmark.

Across all groups, low standard deviation, low variance and high percentage of cohesive failure were observed. The CPA prepared surface showed no statistical drop in performance from 0 hours to 72 hours, however there is a minor median drop of 13% after 168 hours (or 7 Days). This indicates treated parts could be stored for 72 hours before bonding and with no loss in bond performance, while after 1 week there is indications of a minor loss in strength. Significantly, it should be noted all CPA prepared surfaces remain above the 0-hour benchmark of mechanical abrasion (hand sanding) which is 19.50 MPa.

## Splice-Joint Testing – Developmental Model (Breadboard)

A bonded sandwich splice joints was chosen as the breadboard test for this activity as it incorporated in a single model, composite to core and composite to composite bonding. The testing was performed according to the requirements of ASTM D7249 (2018) which is demonstrated in Figure 3‑4. The test articles consisted of RS36 epoxy resin with M55J carbon fibre bonded with Loctite EA9695 epoxy film adhesive to aluminium honeycomb. The splice plates were bonded with EA9394 paste adhesive. A drawing of the specimens is shown in Figure 3‑3.

A blueprint of a joint

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Figure 3‑3: The design and measurements of the Splice Joint Breadboard test specimen.

For the benchmark specimens, the sandwich bonded surfaces were peel ply prepared, while the splice joint plate bond areas were mechanically abraded. The CPA specimen were treated on the honeycomb bond surface side and on the splice joint bond area. Initially CPA treated on the sandwich bonding side, then sandwich bonded to the core. Then CPA treated the splice joint area and paste bond the sandwich panel to the splice plate using separate curing cycles. Ultrasonic C-scan NDT confirmed the specimen were suitable for testing. The goal was to determine the bending stress and the strength of the splice joint.

A machine with a piece of metal

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Figure 3‑4: The breadboard splice joint test set up.

### Breadboard Results

The results shown in Figure 3‑5 demonstrate the CPA group achieved a statistically higher face bending stress than the benchmark, meaning a splice joint prepared using the automated CPA process are superior in performance compared to the current approaches utilised in space currently.

A graph of a graph showing different types of stress

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Figure 3‑5: Bar chart presenting the facing bending stress revised results for the benchmark group and CPA Partial Reveal group, note: the Peel-ply group is the peel-ply and hand-sanded group.

## Impact Summary

This activity’s output demonstrates CPA prepared CFRP materials form better bond joints, and superior bond performance compared to the space benchmarks (State of the Art). Additionally, while CPA has the inherent benefits of low consumables and high automation, this activity further demonstrated CPA prepared surface offer process and operational simplification opportunities, with extended shelf life of at least 7 days. Meaning, the future of space with CPA means better assembled CFRP structures, at lower waste, and under simpler manufacturing scenarios. These implications have impact in all aspects of space, including ground, LEO (Low Earth Orbit), and space exploration level of ESA activity.

# Follow-on Activities

The chosen space applications were satellite and platform substructures, and space truss structures in general, some fairings with direct opportunities to expand to satellite frames, particularly for optical/mirror-based satellites. Figure 4‑2 provides some context sourced from ESA own website.

A group of people in white and blue uniforms

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Figure 4‑2: Examples of applications for CPA with Monolithic and Sandwich activities for space applications

### Additional Potential Space Applications

The activity’s results are presently being used to engage with space entities in these three additional areas – however monolithic and sandwich structures such as launcher/satellite fairings are generating the most interest.

* Launchers and some Satellite Fairings
* Metal Fastening inserts (on monolithic)
* Baffle Shell Joints and Tab Joints
* Mechanical Ground Support Equipment (MGSE)

## Future Focus

In undertaking this activity, there were plans to perform truss structure focused work – particularly as modern struts are lightweight, thermally stable (due to low mass), offer high stiffness with unparalleled structural efficiency. An ideal opportunity for CPA capabilities to be realised. However, due to budget constraints, and additionally, fundamental difficulties associated with the off-the-shelf tube dimensions undertaken, significantly more dedicated engineering time was required. It is planned to pursue this aspect of work in a follow-on activity with a space operator, focused on improving their product quality. An activity plan is already in place to bring CPA to TRL 6 with such a space operator.

In addition, there is potential application for CPA in unleashing the inherent conductivity, by using CPA to reveal the electrically and thermally conductive fibre structure. This would allow a primary or secondary structure to perform it primary function, while also, performing the secondary function of electrical and thermal grounding the structure. This area has implication in a wide range of applications including on board telemetry systems.

# Challenges & Proposed Solution

Continuous Improvement (CI) is at the core of Plasma Bound’s culture. Table 51 provides a summary of some key challenges and the corrective actions undertaken in this activity’s execution, with the level of impact on activity timeline or budget indicated – summarised down forty-one lessons learnt. While COVID and the subsequent supply chain backlog did have an impact, over-familiarity with external teams was considered significantly impactful on the activity’s progress. Through the implementation of several actions in Table 51, and additionally, a change in the external activity led, this issue was resolved. Plasma Bound’s R&D Manager summarised the CAPA outcomes down further to “one gets the behaviour one accepts”.

Table 5‑1: Key lessons learnt during the De-risk activity. Note these are high-level summaries, with specific and issues arising in the background of the activity.

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| **Subject** | **Impact Level** | **Actions** | |
| Communications: | Medium | Better communications with all stakeholders. PB project steering group to stop the 'silo' effect of activity execution team and other team members. | |
| Accountability: | Medium | WP leads cannot run away responsibilities after they had agreed to do something. | |
| Project Management: | High | Better Project Management. Regular meetings from the activity start point - internal and external. | |
| Vendor Control: | High | Better vendor control - Statement of Work, reject unsuitable parts. Site visits/inspections to keep vendors on their toes. | |
| Escalation Pathways: | High | Have escalation pathways in place with external parties. Commercial to Commercial communication channels are important activity momentum. | |
| Transparency: | Medium | Question requests/issues/timelines from vendors. Have the awkward conversations early, so how the activity needs to proceed is clear. | |
|  |  |  |  |
| **Key Takeaway from LL Process:** | **One gets the behaviour one accepts.** | | |

The above suggested changes have already helped Plasma Bound in several currently running projects – making even the soft aspect of this activity, fruitful for Plasma Bound.

# Conclusion

Plasma Bound’s patented CPA technology successfully demonstrated capabilities, often exceeding requirements outlined by ESA, to reach TRL 4. In addition, Plasma Bound has already two potential avenues of interested in follow-on activities, which both have meaningful LSI (Large System Integrators) engagement.

Finally, the result from this activity provides Plasma Bound with the data to engage with independent LSIs and provides reasonable assurances of success when testing Plasma Bound’s CPA process in any proposed activities, minimising their risk on a specific use-case test campaign.