

TOSCA 101191394
Manufacturing Processes and Digital **To**ols for more **S**ustainable **C**omposite **A**erostructures

Deliverable D2.1: "Materials and Process Requirements - Summary"

Due date of deliverable: 2025-04-30
Actual submission date: 2025-04-29

Start date of project: 1st January 2025 Duration: 36 months

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Contributions by: ALL

Dissemination Level		
PU	Public	
SEN	Sensitive information	X

TOSCA Project is entirely funded by the European Union, under the topic HORIZON-CL5-2024-D5-01-08 of the Horizon Europe Framework Programme (HORIZON). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

SUMMARY

Deliverable D2.1 defines the main material, manufacturing and process requirements that guide the technological developments within the TOSCA project. The document establishes the specifications needed to develop recyclable vitrimer-based composite aerostructures and to integrate these materials into automated manufacturing, joining, repair, inspection and digitalisation processes. The requirements are intended to support aerospace applicability while maintaining the project objectives related to sustainability, automation, quality control and circularity.

The report follows the complete manufacturing and component life cycle, starting from the development of the vitrimeric matrix and carbon-fibre reinforcement, continuing through prepreg production and AFP manufacturing, curing, joining and repair, and extending to inspection, structural health monitoring and digital-twin-based data management.

1. **Material development and prepreg requirements:**

A central element of TOSCA is the development of an epoxy vitrimer suitable for structural aerospace applications. The vitrimer uses dynamic disulfide chemistry to combine the structural behaviour of conventional thermosets with additional possibilities for welding, repair, reprocessing and recycling. The resin formulation therefore needs to achieve a balance between high thermal and mechanical performance and sufficient dynamic behaviour to retain these functionalities. The report establishes a target glass-transition temperature around 170 °C, together with requirements related to dynamic bond content, viscosity, tack and curing behaviour.

The resin must also be adapted to the subsequent impregnation and AFP processes. For prepreg manufacture, the key requirements concern resin viscosity and wettability, homogeneous resin distribution, controlled resin content and uniform prepreg thickness. The selected carbon reinforcement is a unidirectional high-strength carbon-fibre fabric with a fixation system that preserves fibre alignment during impregnation.

The resulting prepreg is subsequently slit into tapes compatible with AFP. Particular attention is given to tape width and thickness tolerances, fibre alignment and handling characteristics, since these directly influence deposition quality. An important objective is the development of an enduring vitrimer prepreg that can be stored at room temperature and processed at different curing degrees, avoiding the low-temperature storage normally required for conventional aerospace thermoset prepregs.

2. **Automated manufacturing and curing**

The main manufacturing technology considered is Automated Fibre Placement (AFP). The report defines the principal parameters that must be adapted to the vitrimeric tapes, particularly tape/substrate temperature, compaction pressure, deposition speed and tow tension. Appropriate control of these parameters is required to ensure sufficient tack and interlayer adhesion while avoiding overheating, material degradation or fibre misalignment.

The document also identifies the main defects associated with AFP manufacturing. These include gaps and overlaps, fibre-angle deviations, fuzzballs, twisted or missing tows, compaction defects, porosity, wrinkles, tape debonding, thickness variations and thermal defects. The requirements therefore combine process optimisation with monitoring and inspection strategies intended to detect defects as early as possible and support a progressively more automated, zero-defect manufacturing approach.

For consolidation and curing, TOSCA will compare different routes to determine how the curing process affects the final properties of the vitrimer composite. The experimental strategy includes conventional in-autoclave processing and out-of-autoclave approaches, including oven/vacuum and hot-pressure curing. The resulting laminates are to be characterised mechanically, thermally and microstructurally to identify curing conditions capable of maintaining the required aerospace performance while reducing process complexity and energy consumption.

3. Joining and repair

Joining is another important aspect of the project because the reversible chemistry of vitrimers provides opportunities for more easily reworkable composite structures. The primary joining route considered is resistance welding, complemented by induction welding and adhesive bonding where appropriate. For resistance welding, conductive carbon-based heating elements are investigated to generate heat locally at the interface while controlling the narrow processing window of the vitrimer. The project also considers automated manufacturing and deposition of these heating elements, including AFP and FFF-based approaches.

The report additionally establishes requirements for repair and rework of aerospace composite structures. Repair strategies are selected according to damage severity, structural requirements, accessibility and expected recovery of strength, stiffness and durability. The objective is that repaired structures maintain the required load-bearing capacity and damage tolerance over their remaining service life. Conventional approaches such as patches, scarf/stepped repairs and pre-cured doublers are considered together with portable curing technologies suitable for field or depot repair.

4. Inspection, monitoring and digitalisation

Inspection and monitoring are addressed both during manufacturing and during the operational life of the component. During AFP lay-up, the project considers inline optical inspection, particularly photometric-stereo-based fibre-orientation measurement. The inspection system is intended to identify deviations from the nominal fibre orientation and other relevant deposition defects and compare the measured condition with the CAD definition. Integration of inspection directly into the AFP process is considered desirable to avoid additional inspection steps and maintain manufacturing productivity.

During operation, the project develops a Structural Health Monitoring (SHM) strategy focused particularly on low-velocity impact damage and monitoring of repaired areas. Acoustic-emission systems based on embedded piezoelectric sensors are proposed for impact detection, while magnetostrictive sensors are considered for assessing the structural integrity of repaired regions.

These manufacturing and operational data are brought together through the digitalisation and digital twin activities developed within the project. A common manufacturing database is defined to collect information throughout the component life cycle, including part geometry and lay-up, material properties, AFP process information, inspection results, welding/bonding data, operational sensor information and repair records.

The digital twin therefore acts as a central link between design, material production, manufacturing, quality control, operation and repair. Its intended uses include design validation, manufacturing process monitoring, defect correlation, structural health monitoring, predictive maintenance, repair planning and lifecycle traceability. It is also intended to support future certification activities by maintaining a consistent record of material batches, process parameters, inspection results and interventions throughout the life of the component.

5. Demonstrators and overall validation

All these requirements converge in two representative eVTOL demonstrators. Use Case 1 is based on an external engine cowling/duct section with a curved skin and circumferential stiffeners, manufactured by AFP and joined using resistance welding. Use Case 2 is based on a rudder section comprising skins, a leading edge and an internal bulkhead, with AFP manufacturing followed by resistance welding, induction welding and adhesive bonding. The demonstrators are therefore designed to integrate and validate the main TOSCA technologies rather than to evaluate each development independently.

Finally, the report establishes Key Performance Indicators (KPIs) covering material performance, room-temperature storage of the vitrimer prepreg, AFP productivity, inspection speed and resolution, defect detection, manufacturing efficiency and structural-health-monitoring capabilities. These KPIs provide the reference against which the developments performed during the subsequent work packages will be evaluated.

Overall, D2.1 serves as the technical baseline for the TOSCA project, linking the development of recyclable vitrimer composites with their industrial processing and eventual aerospace application. Rather than focusing on a single technology, it defines the requirements for an integrated manufacturing chain in which material formulation, prepreg production, automated lay-up, alternative curing, joining, repair, inspection and digital tools are developed together. The final objective is to demonstrate composite aerostructures that combine high performance with increased manufacturability, repairability, recyclability, process automation and lifecycle traceability.