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

Deliverable D3.2: "Curing Process Implementation – Summary"

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SUMMARY

Deliverable D3.2 addresses the definition, implementation and validation of curing strategies for the TS-1 vitrimer-based composite material system developed within TOSCA. The work bridges the material formulation activities of Task 3.1 with subsequent manufacturing activities, establishing processing conditions that allow the material to be used through different manufacturing and consolidation routes. Particular attention is given to the interaction between the material state, AFP processing conditions, curing temperature, pressure and time, and their influence on final laminate quality and performance. The study considers different manufacturing scenarios, including conventional hand lay-up, automated fibre placement (AFP), autoclave curing, oven curing and hot-press consolidation. The overall objective is to identify curing strategies that are technically robust and compatible with different industrial applications while also exploring more flexible out-of-autoclave processing routes.

1. Curing strategy and material behaviour

The curing strategy was developed taking into account the different processing states of the TS-1 vitrimer material. A distinction is made between the tacky prepreg, suitable for conventional lay-up, and the enduring prepreg/tape, which has progressed further in cure and is intended particularly for AFP processing. The enduring state provides improved handling and room-temperature stability but also presents higher viscosity and reduced resin flow, making consolidation more challenging. Consequently, the curing cycles and required consolidation pressures need to be adapted to the state of the material.

Different processing routes were therefore defined. A conventional route was established for tacky prepreg consolidated and cured using oven or autoclave. A second, hybrid route involved compacting the tacky prepreg until reaching the enduring state and subsequently consolidating it under pressure. Finally, the main TOSCA route considered enduring tapes deposited directly by AFP and subsequently consolidated using autoclave or hot press. These approaches provide flexibility for manufacturing reference panels as well as panels intended for welding, recycling and subsequent project activities.

Rheological analysis was used to define the corresponding thermal cycles. For tacky prepreg, a two-stage cure was established to first reduce viscosity and promote resin flow and fibre wetting before completing the curing reaction at higher temperature. For enduring material, the cycle was adapted to its substantially higher viscosity, with an initial consolidation stage followed by final curing at 180 °C. The results showed that, although resin flow is more limited in the enduring state, adequate consolidation can still be achieved when sufficient compaction is provided.

Additional DSC characterization confirmed the effectiveness of the selected cure conditions. The material reached an average T_g of approximately 188 °C and a calculated degree of cure close to 99.8%, with very low residual reaction enthalpy. Optical microscopy also showed generally uniform fibre distribution and adequate impregnation, supporting the robustness of the defined thermal cycles.

2. Conventional processing: autoclave versus oven

One of the main experimental studies compared hand lay-up panels cured using autoclave and vacuum-only oven processing. Both tacky and enduring material states were investigated to assess the influence of curing route and consolidation pressure on final laminate quality. The oven panels were consolidated under vacuum, whereas the autoclave panels were processed under significantly higher external pressure.

The results clearly demonstrated the importance of consolidation pressure. Autoclave-cured panels showed better-defined ply stacking, lower void content, more uniform resin distribution and generally improved

mechanical properties. In particular, the autoclave-cured tacky panel achieved substantially higher interlaminar shear strength and flexural performance than the corresponding oven-cured panel. Fibre volume fractions in the autoclave panels were also close to typical aerospace values, whereas the oven-cured tacky panel showed significantly poorer consolidation.

In contrast, the T_g values remained relatively similar for all panels, approximately 173 - 178 °C, regardless of the curing route. This indicates that the differences in mechanical performance were primarily associated with consolidation quality rather than insufficient curing.

Additional oven trials were therefore introduced to investigate whether out-of-autoclave consolidation could be improved. These trials examined the influence of resin bleed control and pressure distribution using approaches such as resin dams and caul plates. The work confirmed that limiting resin loss alone was not sufficient; uniform pressure application across the laminate remained essential. Further optimisation of bagging and tooling was consequently identified as necessary before vacuum-only oven processing could be considered a reliable alternative.

3. Hybrid processing route

A hybrid processing route was also developed to provide panels for preliminary welding and recycling activities. In this approach, tacky prepreg was first compacted and partially cured until reaching the enduring state, followed by final consolidation under pressure. This route was successfully validated through panel manufacturing. The resulting laminates showed good consolidation, without significant porosity detected through microscopy, and reached a T_g consistent with full curing. The fibre volume fraction was slightly below typical aeronautical values, mainly due to the initial resin content of the prepreg, while the ILSS remained within the expected range for the selected reinforcement configuration. The results confirmed that this hybrid approach can provide a practical alternative when AFP-manufactured material is not required.

4. AFP manufacturing of vitrimer tapes

A major part of the work focused on establishing the feasibility of manufacturing TS-1 vitrimer composites using Automated Fibre Placement. The AFP trials confirmed that enduring vitrimer tapes can be deposited automatically, but they also highlighted specific processing challenges compared with conventional aerospace prepregs. The most significant issue was the delayed activation of tack after heating, which reduced the available processing window between heating and deposition. Tape-width variability and tow stability also influenced deposition quality. Stable manufacturing conditions were achieved at relatively low deposition speed, approximately 0.1 m/s, together with controlled compaction force and thermal activation. These results demonstrate AFP feasibility but also confirm that the material requires careful optimisation of temperature, speed, compaction and tape handling.

5. Curing of AFP panels: hot press versus autoclave

AFP-manufactured panels were subsequently consolidated using hot press and autoclave curing to assess the effect of pressure and curing route on laminate morphology. The hot press, operating at significantly higher pressure, produced visually flatter panels with lower and more uniform thickness. Autoclave panels showed slightly greater thickness and more visible fibre and lay-up patterns at the surface. However, tactile and visual assessment indicated that the autoclave panels appeared more compact and structurally robust internally.

Some localised defects were also identified in the hot-press panels, including a crack-like feature in one 90° laminate. These observations indicate that surface flatness alone cannot be used as an indicator of laminate quality. Instead, the preliminary results suggest a trade-off between geometric uniformity, promoted by the higher pressure of the hot press, and internal structural consistency. Further microscopy, thermal and mechanical characterization was therefore identified as necessary to fully compare the two routes and was presented on deliverable 5.1.

6. Overall conclusions and next steps

Overall, the deliverable demonstrates that the TS-1 vitrimer system can be processed successfully through several manufacturing and curing routes, including conventional hand lay-up, hybrid processing and AFP. The thermal cycles defined for both tacky and enduring material states were shown to achieve adequate curing, and the results consistently identify consolidation pressure and pressure uniformity as key parameters controlling final laminate quality.

Autoclave processing currently provides the most reliable consolidation for hand lay-up panels, while oven curing requires further optimisation if it is to become a viable out-of-autoclave alternative. AFP processing has also been demonstrated, although the distinctive tack and handling behaviour of the vitrimer tapes requires a narrower and more carefully controlled deposition window.

The ongoing activities focus on completing the characterization of AFP-manufactured panels through optical microscopy, DSC, DMA and mechanical testing, together with further optimisation of out-of-autoclave processing. These results will provide a more complete comparison between autoclave, hot-press and oven routes and support the selection of appropriate manufacturing strategies for subsequent TOSCA demonstrators and applications.