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Manufacturing Processes and Digital Tools for More Sustainable Composite Aerostructures

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Coordinator:
Christian Eitzinger
Profactor

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1. OBJECTIVE

The objective of this report is to present the results obtained within Task 3.3, focused on the development of joining processes for composite structures manufactured with vitrimer-based resins in the framework of the TOSCA project.
One of the main advantages associated with vitrimer materials lies in their reprocessability. Thanks to the presence of dynamic covalent cross-links within the polymer network, vitrimers can undergo bond exchange reactions when exposed to elevated temperatures. This characteristic enables the possibility of joining different components through welding, which represents a significant advantage for the manufacturing of aeronautical structures. In conventional thermoset composites, joining operations typically rely on mechanical fastening or adhesive bonding, which may introduce additional weight, stress concentrations, and increased manufacturing complexity. In contrast, welding-based joining approaches offer the potential for more efficient manufacturing routes, reduced part count, and improved structural integration.
Despite the theoretical reprocessability of vitrimer systems, their behaviour differs significantly from that of thermoplastic polymers. Unlike amorphous thermoplastics, vitrimer networks do not exhibit a free flow of polymer chains when heated above the glass transition temperature. Furthermore, in contrast to semi-crystalline thermoplastics, vitrimers do not present a well-defined melting temperature at which the material transitions into a fully molten state. Instead, the topology rearrangement enabled by dynamic cross-links allows gradual stress relaxation and network reconfiguration. As a consequence, the development of suitable welding strategies for vitrimer-based composites requires a dedicated investigation of the processing window and joining parameters. For this reason, the main objective of Task 3.3 within the TOSCA project is the development and optimisation of joining processes for this vitrimer system. Particular emphasis is placed on resistance welding techniques based on embedded heating elements, which enable localized heating and controlled activation of the dynamic bond exchange reactions required for joining.

Accordingly, this deliverable mainly focuses on the development of welding processes for vitrimer-based composite laminates. However, adhesive bonding approaches are also considered and included in this report in order to provide a broader assessment of potential joining strategies. Furthermore, since one of the key objectives of the TOSCA project is the development of automated manufacturing solutions for composite structures, several activities within this task are dedicated to the automation of the resistance welding process. In particular, experimental investigations have been carried out to evaluate the automated manufacturing of heating elements and their integration onto composite laminates, as well as the influence of process parameters on welding performance.

2. CONCLUSIONS

The results obtained within Task 3.3 of the TOSCA Project highlighted that it is not possible to achieve a satisfactory welded joint between laminates based on the vitrimer formulation developed within the project when the material is fully cured. This limitation was consistently observed in both resistance welding and induction welding trials. In both cases, the inability to obtain a welded interface with satisfactory quality was attributed mainly to the insufficient consolidation pressure available during processing and to the extremely narrow processability window of the material, which makes it very difficult to achieve a temperature distribution capable of activating the dynamic crosslinks without simultaneously causing thermal degradation.

Indeed, welding is an inherently rapid in-situ process performed outside a controlled thermal environment, making precise temperature control particularly challenging. Maintaining the material within the suitable processing window throughout the entire joining process is therefore difficult. Processing time also emerged as a critical factor since the material, as emerged from the study on the TS-1 vitrimer's stress-relaxation, should ideally remain under processing conditions for a duration corresponding to approximately ten times the polymer relaxation time. Such times can become excessively long; for example, at 190 °C the recommended processing time would be approximately 24 minutes, which is incompatible with the productivity advantages that welding technologies are expected to provide within the manufacturing chain of aerospace components.

Furthermore, rheological characterization demonstrated that the vitrimer does not exhibit significant flow above its glass transition temperature, unlike thermoplastic materials. The absence of material flow not only limits the possibility of welding rough or uneven surfaces—where achieving intimate contact is essential—but also makes the process particularly challenging for complex geometries, where local gaps or imperfect contact conditions may arise due to manufacturing tolerances.

Considering these limitations, together with the poor welding performance obtained for fully cured laminates and the encouraging results achieved with laminates in the "Enduring stage," it can be concluded that future welding activities within the TOSCA Project should focus on the joining of partially cured laminates and on the integration of such joining strategies within the overall manufacturing chain of aerospace components.

On the other hand, the activities related to the automated AFP deposition of heating elements showed promising results. Once the curing stage at which the material will be welded within the TOSCA Project is definitively established, welding trials will be carried out using these AFP-deposited heating elements, and their performance will be compared with that achieved using manually positioned and previously consolidated heating elements.