SALIENT

Safer, Lighter, Circular, Smarter

» DELIVERABLE D3.4

MULTI-FUNCTIONAL DESIGN AND OPTIMIZATION OF MATERIALS

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DISSEMINATION LEVEL

Abbreviation	Meaning	
PU	Public, fully open (Deliverables flagged as public will be automatically published in CORDIS project’s page).	[X]
SEN	Sensitive, limited under the conditions of the Grant Agreement.	

LIST OF ABBREVIATIONS

Abbreviation	Meaning
AF	Aramid fibres
AL	Aluminium
CF	Carbon fibres
CFRP	Continuous fibre reinforced plastic
DFT	Density functional methods
DIN	Deutsche Industrie Norm
DoE	Design of experiment
EN	European Norm
FEA	Finite element analysis
FES	Front-end structure
FMC	Fiber mass content
FRP	Fiber reinforced plastic
PA6	Polyamide 6
PP	Polypropylene
MAH	Maleic anhydride
MD	Molecular density
NW	Non woven
TP	Thermoplastic
TPR	Thermoplastic rubber/elastomer
UD	Unidirectional
WP	Work Package

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1. EXECUTIVE SUMMARY

The objective of T3.3 was to develop a multi-level, multi-functional optimization method for the developed thermoplastic continuous fibre reinforced plastic (TP CFRP) including effects of processing, damage tolerance and lightweighting. In the first part of this report is introduced the theoretical base of the multifunctional optimization of the materials and the main techniques used. In the second part of this report is discussed the result obtained on the materials developed into SALIENT project. Based on the developed TP CFRP in T3.1 a unidirectional tape (UD tape) was investigated for ideal properties and processability to achieve optimized properties which is required in crash relevant applications like the front-end structure (FES). Especially an innovative and advanced TP CFRP material was developed which has a high level of energy absorption in crash load cases. Within the optimization the multi-functionality aspects of the optimization are taken into account and the alignment with the WP2 design criteria is considered and controlled. The main results of the project are optimized materials in terms of stiffness, strength, ductility and lightweight construction.

2. INTRODUCTION

Introducing a comprehensive research project SALIENT to craft a pioneering multi-level, multi-functional optimization method for novel materials. In the quest to harness the full potential of these advanced materials, an array of essential attributes will be considered, including strength, stiffness, geometric intricacies and ductility. A collaborative effort among various experts, this research consortium comprises **UNN**, **tPE**, **FRA**, **CID**, and **CRF**, each with a unique focus and contribution to the overarching goal. **UNN**, **tPE**, and **FRA** are dedicated to the analysis of how microstructural adaption of the material influence damage evolution under diverse loading conditions. Their work is pivotal in fine-tuning composites for enhanced performance, damage tolerance, and the pursuit of lightweighting. Complementing these efforts, **CID**, with its expertise in design criteria, ensures that the optimization aligns seamlessly with the objectives of WP2. As the project unfolds, **CRF** will delve deep into the intricacies of multi-functionality, providing valuable insights into how these novel materials can serve a multitude of purposes. Through these collaborative endeavours, this task promises to optimize the realm of materials development, with its holistic implications and innovative approach to optimization.

Multifunctional materials are materials that have several properties or functions that are required simultaneously. This is the case of the materials developed in the SALIENT project, which must have different mechanical properties for the behaviour in crash, in addition to the guarantee specific requirements of sustainability and lightness.

In general way therefore into the design and optimization of multi-functional materials we must do some several fundamental considerations; For first is necessary identify the desired functions that the material needs to exhibit and establish the priorities respect the different functions. Next, is necessary to select the appropriate material properties that can enable those functions. The achieving multiple functionalities involves trade-offs, as improving one property might negatively affect another. Balancing these trade-offs is a critical aspect of material design. Based on the identified functions and desired property combinations, you can select suitable base materials and their combination. The combination of the basic constituents determines the microstructure of the materials; The optimization of the microstructure represent the fundamental phase for determining the final desired properties that will be verify with experimental tests and virtual simulations of the components and systems.

Based on the specific needs and performance criteria of the FES defined in WP1, advanced materials were developed in T3.1. Their properties are to be multi-level, multi-functional optimised within the framework of T3.3. Therefore, material parameters must adjust according to the requirements of the component, especially high strength, high energy absorption, high ductility, and a good lightweight. Several attributes and properties of the TP CFRP were included in the optimization like matrix-, fibre- and laminate modifications. The project partners were analysing the effect of influences of different material levels of damage evaluation to optimize the composites' performance, damage tolerance and lightweighting.

3. MULTI-FUNCTIONAL DESIGN AND OPTIMIZATION OF THE MATERIALS DEVELOPED IN SALIENT

3.1 TP-CFRP

3.1.1 Methods of material optimization

Improving the energy absorption of brittle fibre-reinforced plastics (FRP) is important to increase their impact strength and crash resistance. Brittle materials tend to fail under high loads by fracturing without warning and thus breaking without sufficient energy absorption. There are optimisation methods on different material levels which can be used to make the material behaviour more ductile. These material levels start with the modification of the starting materials, i.e. the modification of the matrix and the selection of suitable fibres. The matrix of an FRP material can be modified by adding more ductile polymer or elastic modifiers. This increases the toughness of the matrix and contributes to energy absorption. In addition, the choice of fibres can influence energy absorption. For example, hybrid fibre systems containing both stiff and tough fibres can be used to increase the overall toughness of the material. The next material level that can be theoretically adapted is fibre-matrix interactions. By optimising the adhesion between the fibres and the matrix, energy absorption can be improved. Better adhesion prevents fibres from detaching and promotes uniform load distribution. The highest level of material alignment is at the composite level. Here, on the one hand, a significant improvement in the ductility of the material can be achieved through improved fibre alignment as well as the addition of crack-stopper layers. The load-specific alignment of the fibres in an FRP component can influence the impact strength through high force absorption with concurrently long deformation paths. Pure unidirectional layers (UD) of FRP show extremely high strengths, especially in their main fibre direction. However, loads that deviate slightly from the main fibre direction can lead to ultimate failure without further energy absorption. The use of crack-stopper layers leads to a supporting effect of the fibres even after the first layer failure and thus to a redistribution of the loads. in total, the FRP can absorb a significantly higher energy, i.e. without these specific layers.

By conducting a DoE analysis, the following Table 1 shows an evaluation of the individual measures to assess which measures are most effective and should therefore be continued within the framework of the project. If one evaluates the five possible modifications by means of evaluation variables such as influence on ductility, influence on other properties, feasibility, costs in the end product as well as lightweight factor, three preferred variants emerge, including matrix modification, orienting the fibres and using a crack-stopper layer. The matrix modification was rated particularly positively. By increasing the toughness of the base polymer, the overall toughness of the composite can be adjusted without significantly reducing other properties such as strength or stiffness. Since the additives suitable for the plastic can be mixed into the base polymer in small quantities directly in the extrusion process, both a realisation and the influence on the costs in the later component are marginal. A preferred variant according to the evaluation matrix is the load-appropriate design of the fibre orientation. Reorienting the fibres can significantly increase the ductility of the composite, but also a result in an adjustment of the overall stiffness and strength. However, in terms of additional costs and the lightweight factor, this variant is to be favoured. Since no material engineering investigation is necessary for this variant, reference is made here to WP5, in which an ideal laminate structure is to be determined by means of simulation. The last preferred option is the use of crack-stopper layers. In this variant, thin layers with, for example, a random fibre distribution are used to prevent cracks from growing. The advantage is that the other layers can be aligned according to the load. The use of an additional layer marginally reduces the lightweight factor, but generally does not lead to an increase in the cost of the product, since crack-stopper layers can be produced in a large-scale production process such as the needle fleece process.

Table 1: Evaluation of modification options with regard to various assessment variables

	Influence on ductility	Influence on other properties	Feasibility	Lightweight factor	Costs in the end product
Matrix modification	+	+	+	+	+
Fibre modification	+	-	+	-	+
Fibre-Matrix modification	+	-	-	+	+
Orientations of fibres	+	-	+	+	+
Crack-stopper layer	+	+	+	-	+

+... postiv, -...negativ

3.1.2 Matrix modification

Polyamide 6 is already used in a variety of automotive applications due to its good strength and stiffness in processing with good processing properties. However, PA6 can tend to be brittle when dried, which is why this material is rarely used for impact loaded components. Impact modifiers can improve these properties and increase resistance to impact. This effect can be achieved in various ways. One method is creating a plastic blend with a more impact-resistant material from groups such as elastomers, elastomer-modified copolymers and classic thermoplastics. However, it is essential to ensure chemical and thermal compatibility between the base polymer and the additivities polymer to prevent polymer segregation or degradation. Adding glass fibres to polyamide is another method of improving impact strength while maintaining the stiffness of the composite. This is particularly useful in applications where stiffness and impact resistance are required. For this purpose, **UNN** has selected and provided a PA6 with short glass fibre reinforcement, which is to be used in certain proportions to produce the UD tape. Based on the viscosity results shown in Figure 1 of the material at a shear rate of 100 1/s, it's evident that the material is excessively viscous for a direct impregnation method. Consequently, no tests were performed to enhance the material's impact resistance.

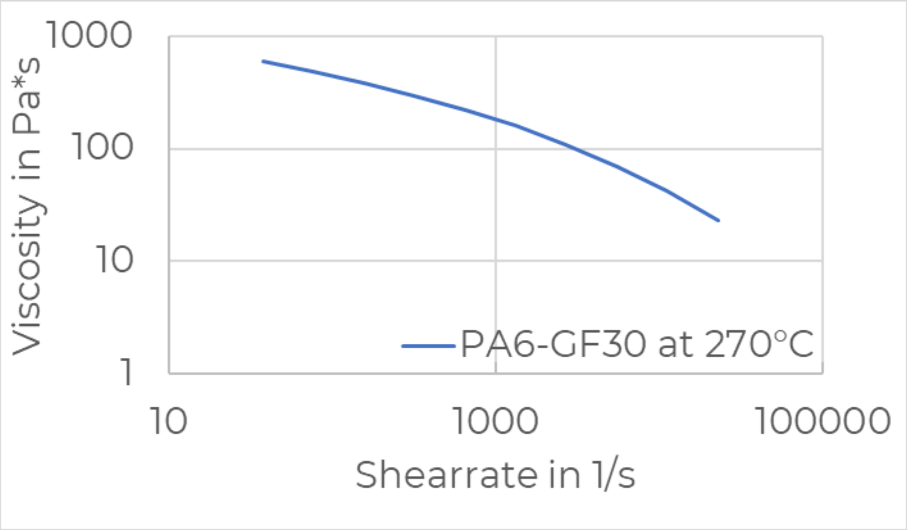


Figure 1: Viscosity-shear rate-graph of a PA6-GF30 at 270°C

For the modification of the matrix to achieve increased impact strength, the focus was therefore on the production of a blend with an impact-resistant plastic. The focus of the investigations was to find a plastic that is both thermally and chemically compatible with PA6 and has a sufficiently low viscosity so that the manufacturing process of the tape is not negatively affected. Due to their hyperelastic behaviour, the focus was on rubber elastomers and elastomer-modified copolymers, which has a particularly positive effect on impact strength. Rubber elastomers such as ethylene-propylene-diene rubber can be used as impact modifiers for polyamides. They can be blended into the polymer matrix in the form of particles or as a dispersion. In both cases, the viscosity is increases by the addition of the crosslinked plastic. Thermoplastic elastomers (TPR) are elastomers that behave like classic representatives of elastomers at room temperature, but become deformable when heated. The combination of these two properties is to be used for impact modification of PA6. For initial investigations, two types of impact modifiers were selected that were both thermally and chemically compatible with the selected PA6. However, these two modifiers (Mod) differ in their hardness value, in which Mod 1 has a Shore hardness of 71 and Mod 2 has a Shore hardness of 79.

The first step is to investigate the influence of the modifiers on the plastic's properties. For this purpose, the PA6 was additivated with the two modifiers in 4 mass steps in the injection moulding process. The non-additivated PA6, which was produced with the same processing parameters, serves as a reference for the evaluation parameter. The objective of the initial research was to establish the optimal ratio of modifiers and PA6 prior to commencing production of the UD tape. Figure 2 shows the samples with different proportions of modifiers. Apart from a reduction in translucency with increasing modifier content, no external changes e.g. in the surface or at the roughness can be seen in the samples. Modifier 2 also shows a discolouration of the plastic. It is suspected that the processing of the modifier together with the PA6 led to a thermal degradation of the plastic.

Figure 2: Tensile samples of polyamide 6 with different amounts impact modifiers

The primary goal of incorporating a modifier is to enhance the impact strength and energy absorption of PA6. However, it may significantly compromise the material's static mechanical properties. Therefore, it was decided to conduct material tests, both static and dynamic, in order to evaluate how the modifier is affected by strain rate. The static tests involved a tensile test, carried out in accordance with DIN EN ISO 527-2, with tensile strength being the chosen evaluation parameter. For the dynamic tests, a Charpy impact test in accordance with DIN EN 179-2 was performed using notched samples and the impact energy was evaluated. The results for the static and dynamic tests are shown for modifier 1 in Table 2 and for modifier 2 in Table 3.

Table 2: Testing results of PA6 with different amounts of modifier 1

	Mod 1 PA6-X0	**Mod 1 PA6-X0.5**	**Mod 1 PA6-X1**	**Mod 1 PA6-X2**	**Mod 1 PA6-X3**
Strength in MPa	56,0	49,3	47,2	41,4	32,9
Notch impact work in kJ/m²	33,3	34,2	35,3	127,0	117,3

Table 3: Testing results of PA6 with different amounts of modifier 2

	Mod 2 PA6-X0	Mod 2 PA6-X0.5	Mod 2 PA6-X1	Mod 2 PA6-X2	Mod 2 PA6-X3
Strength in MPa	56,0	51,8	49,2	43,5	27,1
Notch impact work in kJ/m²	33,3	21,6	24,2	25,6	28,3

Modifier 1, with a Shore hardness of 71, exhibits a moderate reduction in tensile strength in static tests as the proportion of the modifier increases. Nonetheless, impact energy clearly increases. Particularly, the impact energy nearly quadruples the original value for a modifier proportion of X2. Modifier 2, with a Shore hardness of 79, exhibits decreases in both tensile strength and impact energy, which is contrary to the outcomes of the tensile strength by modifier 1. Possibly the unintended properties may be attributed to the excessively high hardness of the modifier or potential thermal degradation during the processing.

Following encouraging preliminary results, trials were scheduled for manufacturing UD tapes with the impact modifier Mod 1. To examine the impact of the modifier on thermoplastic continuous fibre-reinforced plastic, two batches were produced based on the preliminary tests - batches X1 and X2. Furthermore, a reference batch was produced without any impact modifier. 10 kg of each experimental variant (X0, X1, X2) were produced in 25 mm width, based on tapes developed in T3.1. The resulting tapes were cut into strips measured 260 mm in length and placed manually in the pressing tool. To ensure optimal fibre alignment, the layers were fused together using a thermal fusing process. Finally, a plate was created from the stack using process parameters comparable to those established in T3.2. Figure 3 shows the process of manufacturing the plates.

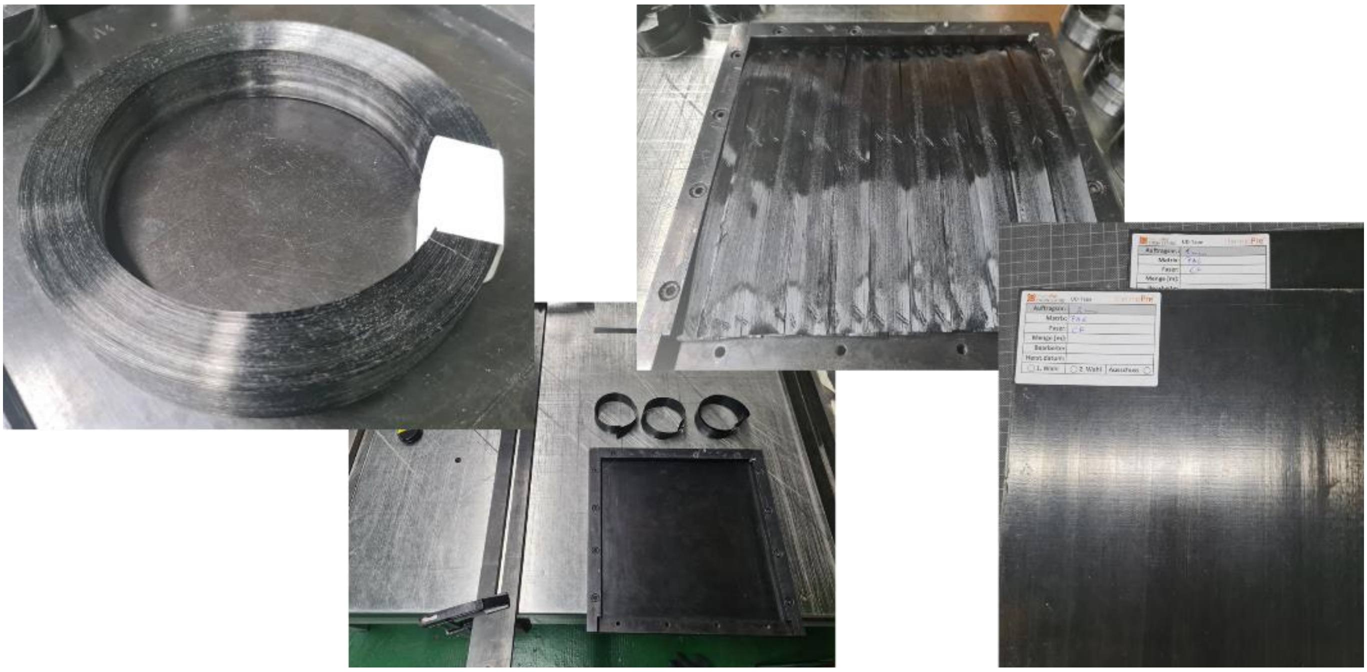


Figure 3: Manufacturing process of the test panels, from left to right: UD tape with modifiers, cutted tapes and pressing tool, UD tapes placed in the tool and thermally fixed, finished pressed panels

Microscopy samples were taken from each organoplate to assess the quality of the plates produced. These microscopies are shown I nFigure 4. In the left figure, the homogeneity of the composite and the high packing density can be clearly seen. The right figure shows a detailed image for the good impregnation of the carbon fibres with matrix. Overall, it can be said that the quality of the organo sheets is very good. These good results were observed with all three material combinations.

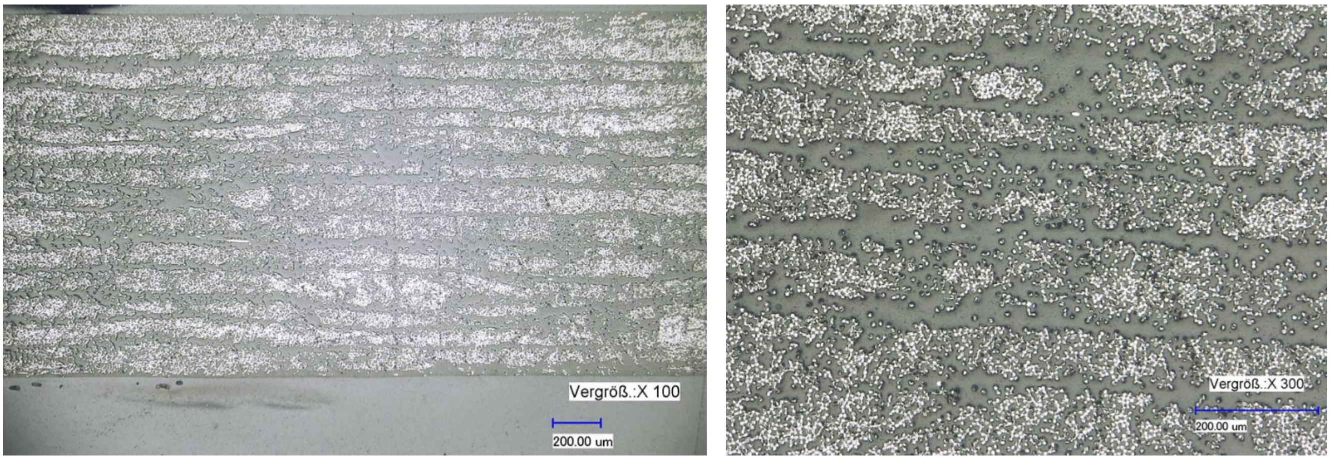


Figure 4: left: Microscopy with 100x magnification, total thickness of the composite; right: Microscopy with 300x magnification, detail of the composite.

In comparison to the mechanical characterisation of the preliminary tests, both static and dynamic tests were also carried out to determine the influence of the impact modifier on the UD-tape. For the static tests, bending tests were carried out according to DIN EN ISO 14125 and for the dynamic tests Charpy impact tests according to DIN EN ISO 179-2. Both tests were applied with bending loads, which generate tensile, compressive and shear loads in the specimen. By using these two test methods an influence of the strain rate can been seen. In the static bending tests, the bending strength is evaluated, while the dynamic tests are evaluated in particular with regard to the impact energy.

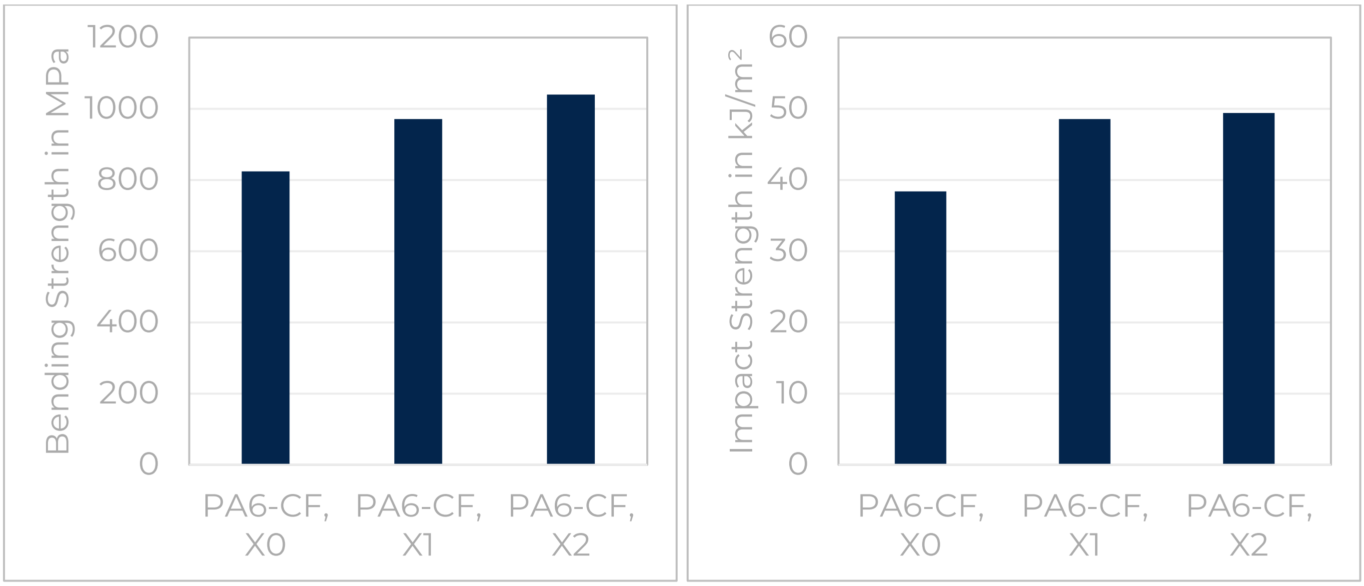


Figure 5: left: results of the bending test; right: results of Charpy impact tests

In contrast to the tests without fibre reinforcement, the results of the static tests show an increase in strength with an increasing proportion of impact modifier. Further research is required to investigate the mechanics in play. This possible correlation may be attributed to the load-transmitting matrix's increased toughness, which redistributes load to undamaged areas when the fibres first fail. A similar trend is observed in the dynamic impact tests, where an increase in the impact modifier proportion results in increased impact strength. However, in contrast to the static tests of the PA6-CF, an increment in the modifier from X1 to X2 leads to a smaller increase in the impact energy. In brief, modifying the matrix resulted in up to a 29% increase in ductility compared to non-modified PA6-CF tape.

3.1.3 Crack-stopper layer

As described earlier, a crack-stopper layer is designed to prevent an initial failure which could result in an ultimate failure of the entire structure. The research approach is based on inserting a layer of randomly oriented fibres between layers of UD-tape, which can endure a failure and redistribute the load-bearing capacity to undamaged regions. As a crack-stopper layer, a needle fleece is used which consists of 25% carbon fibres, 25% aramid fibres and 50% PA6 fibres. The needle fleece can thus be regarded as a solitary fibre composite which, like the UD-tape, is pressed and consolidated into an FRP. The reinforcing fibres used are long fibres with a length of 50 mm. The combination of aramid and carbon fibres results in a material that is impact resistant, stiff and strong at the same time. The used nonwoven (NW) produced in a needling process is shown in Figure 6.

Figure 6: left: Continuous roll of nonwoven made from PA6, aramid and carbon fibers, right: Detailed representation of the random fiber orientation of the nonwoven

The nonwoven was created with a basis weight of 1000 g/m², resulting in an approximate thickness of 1 mm when fully consolidated. To ensure a symmetrical stack of layers, the crack-stopper layer is placed in the middle of the laminate, forming a sandwich structure. This structure is shown in Figure 7. Microscopy images were taken to assess the quality of the organic sheets. (Figure 7). These show well that in the cover layers consisting of PA6-CF UD tapes only 0° oriented fibres with a high packing density and good impregnation are present. The core layer consists of randomly oriented fibres, lower packing density. Due to the characteristic of non-woven with regard to the multitude of crossing fibres, it is also possible to recognise the cut longitudinal as well as parallel fibres. The material divergence in the core can also be recognised by the different fibre diameters.

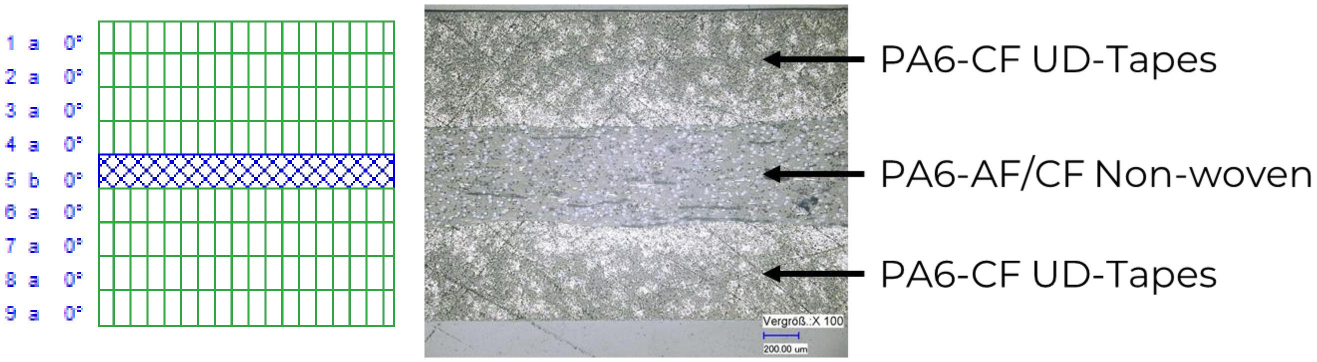


Figure 7: Left: Layup consisting of a) PA6-CF plies and b) nonwoven ply; not scaled; right: microscopy of the lay-ip consisting a crack-stop-layer

To ensure the comparability with the results of matrix modification, a flexural test based on DIN EN ISO 14125 for the static characterization of the properties, and based on DIN EN ISO 179-2 for the dynamic characterization of the properties were conducted.

The results from the bending tests show that the structure with the crack-stopper layer increases the bending strength from 824 MPa to 1070 MPa. For a high bending strength, the tensile and compressive strength of the extreme fibres is important, but also the shear strength in the neutral fibre of the laminate structure. The results suggest that the quasi-isotropic fibre distribution of the crack-stopper layer in the neutral fibre can increase the shear strength of the entire laminate. Thus, a higher flexural strength can be achieved with the same tensile and compressive strength of the extreme fibre layers. Under dynamic load testing using Charpy impact, the crack-stopper layer was found to have a significantly positive impact. The impact energy was increased from 28 kJ/m² to 98 kJ/m².

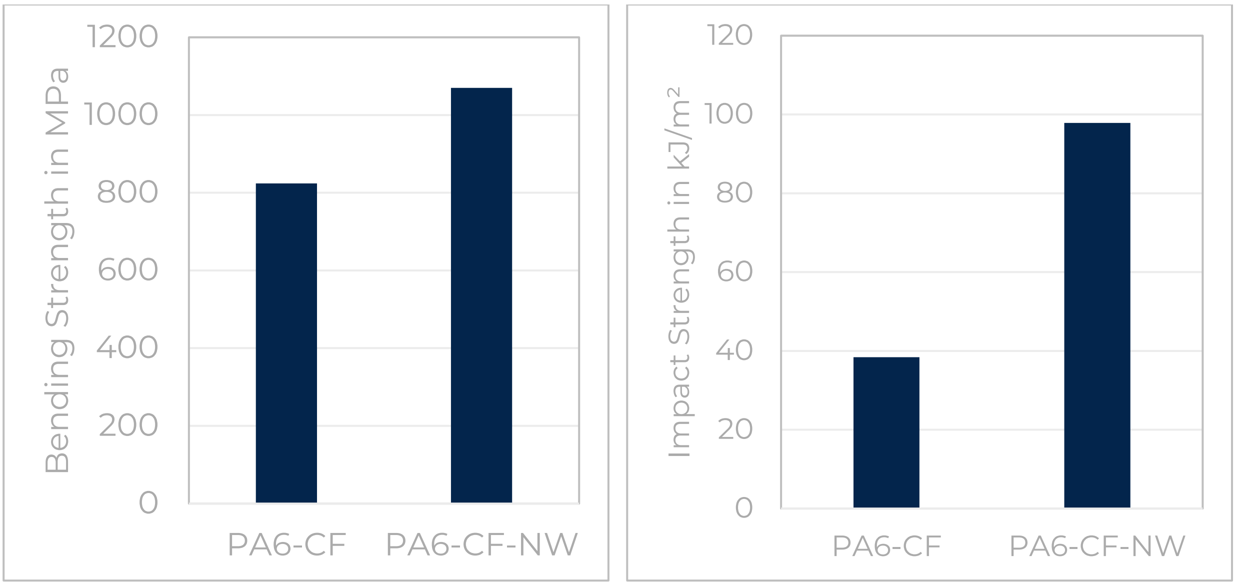


Figure 8: left: results of the bending test; right: results of Charpy impact tests

3.1.4 Comparison of the material optimizations in the crushing test

The energy absorption behavior of composites is challenging to predict due to the complex failure mechanisms that can occur in the material. Various fracture mechanisms have been reported including fiber fracture, matrix cracking, fiber-matrix debonding, and interlaminar damage (delamination), occurring in different combinations and sequences. The development of energy-absorbing composite structures typically necessitates the undertaking of numerous crashworthy substructure tests to ascertain whether the proposed configuration performs as intended.

The primary variables that influence outcomes include the geometry of the structure, material system and loading rate. Crushing tests are valuable in assessing the strength and failure modes of materials, components, or structures under compressive forces. They provide insights into material behavior ductility. Common parameters of analysis of the energy absorption behavior of a crushing structure include the peak force, which is the highest point in the force-displacement diagram, along with the average crush force. The total area under the force-displacement diagram is referred to as absorbed energy. In the following, the results of testing a waved crushing structure under impact dynamic loading are shown.

The test specimen has a sinusoidal segment that was repeated five times on alternate sides relative to the center plane. The specimens were manufactured using the compression molding process. Due to its self-supporting nature, the specimen can deform freely near the crush front, and its three-dimensional geometry can capture most failure modes observed in tubular specimens. The sample lacks any crush release, leading to peaks in the load-displacement diagram.

All tests were conducted at a dynamic velocity of 2 m/s. Specimens were tested vertically on a drop test rig that is placed on a hardened steel surface. At least three specimens were tested for each configuration. In this study, the various modifications of the PA6/carbon fiber material systems were examined. The fiber layers were oriented unidirectionally in the direction of loading.

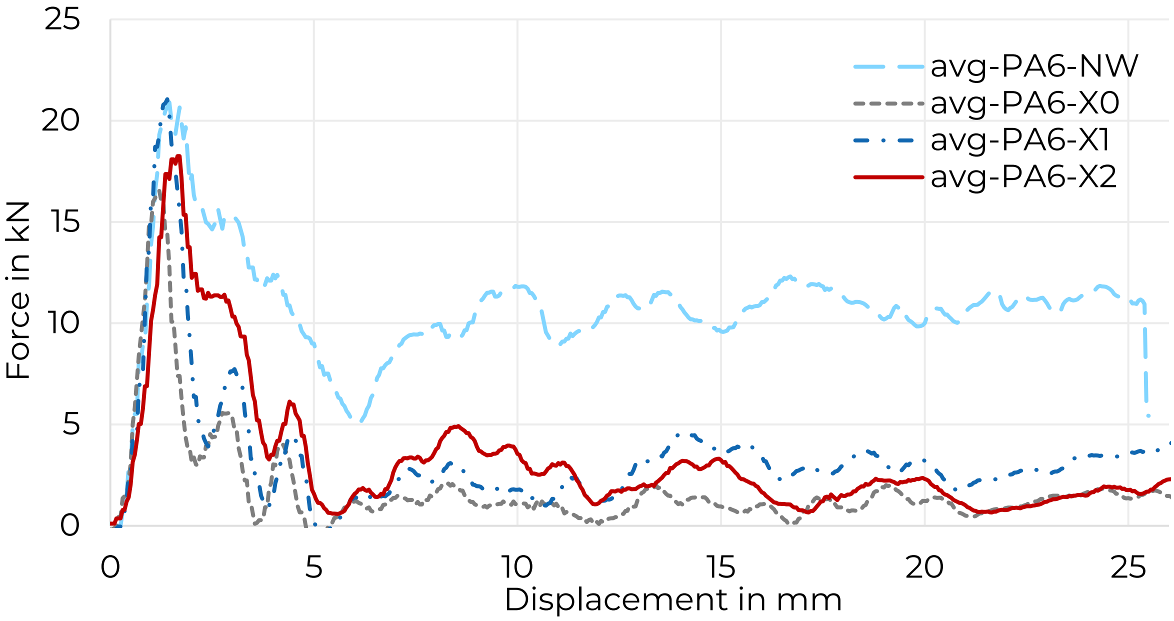


Figure 9: Results of crushing tests with different methods of material optimizations

Figure 9 shows the averaged curves from three test curves. Of particular interest is high energy absorption. This means that after the initial peek, ideal results are characterized by a high force over a long test path. If the materials are compared with regard to this evaluation criterion, an increase in energy absorption is achieved with an increase in the modifier content. This assessment of the force-displacement curves is supported by the absolute values of the energy absorption corresponding to the area under the curve, which are shown in Table 4. This clearly shows that the addition of an impact modifier can increase the energy absorption from 46 J to 85 J, which corresponds to a percentage increase of 74%. A significant increase in ductility was achieved by using a crack-stopper layer. The force-displacement curves in Figure 9 show very clearly that the force level can be maintained at an average of 10 kN after the peak force of the impact. This results in an absolute energy absorption of 270 J. Thus, the energy absorption could be increased by the factor 5.8.

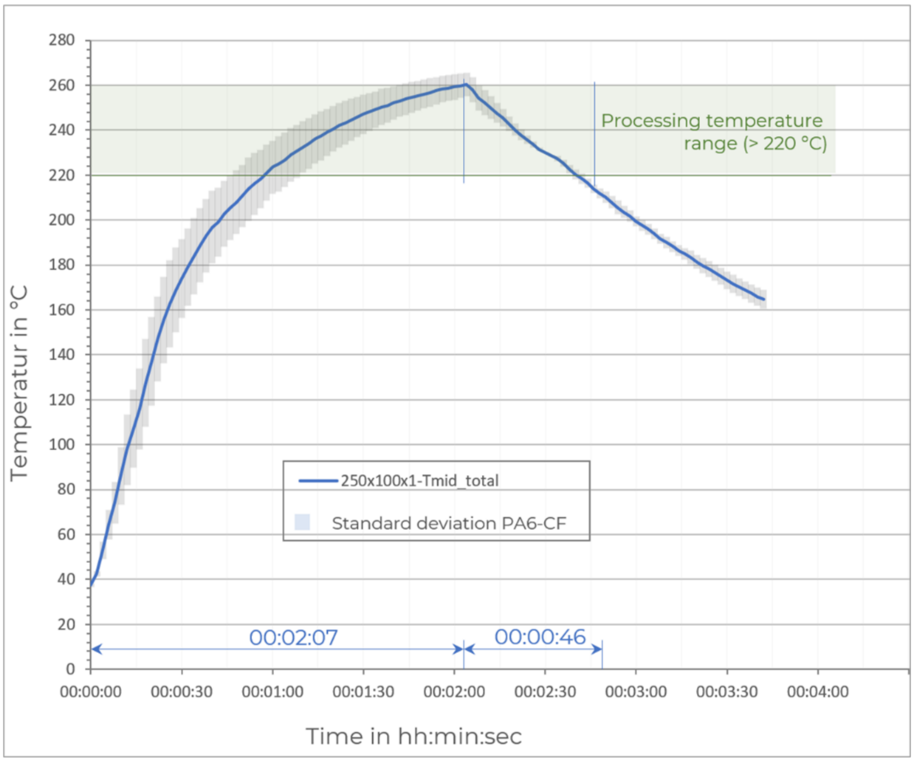
Table 4: Energy absorption of different material optimizations

	PA6-CF, X0	PA6-CF, X1	PA6-CF, X2	PA6-CF, NW
Energy absorption in J	46,1	83,0	84,9	269,8

3.2 SMA

The smart material developed in Task 3.1 consisting of an SMA wire integrated in composite showed promising results. Based on the first mechanical tests, parameters to be optimised were defined, which were optimised within the framework of T3.3. Due to the very high thermal conductivity of carbon fibres, the production of composites in particular requires ideal temperature control during preheating and in the pressing tool, but also optimised transfer times between preheating and pressing tool. For this reason, studies were conducted to define optimal processing parameters. The focus was on the temperature of the pre-tempering, the duration of the pre-tempering, optimisation of the temperature during the transfer and the mould temperature. The aim of the investigations was to determine the optimal adhesion between the SMA and the composite as well as the ideal consolidation of the composite.

In order to determine the processing windows of the PA6-CF in 2-stage pressing process, temperature sensors were placed at 4 points of the stack during the heating process. Figure 10 shows the averaged heating curve of the PA6-CF material with an ideal processing window, which starts at 220°C and ideally should not exceed 260°C. The diagram clearly shows that the maximum processing temperature is reached after a heating time of about 2 min. At this point, the heated sample was exposed to ambient air and the time was measured until the temperature is outside the processing window. This results in the maximum transfer time that can be used for the transport between the preheating station and the pressing tool.



b

Figure 10: Heating curve of PA6-CF: mid curve of 4 measurements showing the ideal processing window

Based on the investigations, the following parameters were used for the production of SMA integrated composites:

- Preheating station: 270°C,
- Preheating time: 125 s,
- Transfer time: <30 s,
- Mould temperature: 75°C.

Figure 11 shows the resulting plates with an high surface quality and good bonding between the SMA wire and the composite.

Figure 11: SMA integrated composite plates manufactured with ideal process parameters

In order to finally evaluate the influence of the processing parameter on the mechanical properties of the SMA integrated composite, an SMA integrated composite plate was produced in a variothermal process according to the processing parameters from T3.1. The long exposure to pressure and temperature during the static pressing process ensures that an ideal bond between SMA and composite can be achieved.

The mechanical properties of the materials obtained as result of the two manufacturing approaches was evaluated by means of bending tests at room and high (100°C) temperature. Coupons of nominal dimensions 100 mm x 15 mm x 2 mm were machined from the plates. The test setup and execution were carried out according to ISO 14125, being the most relevant test parameters the following: 80 mm span between supports; 10 mm diameter of the loading edge; 4 mm diameter of supports; 5 mm/min displacement speed (Figure 12). Tests were stopped after evident signs of failure were observed in the samples as well as in the force-displacement curves.

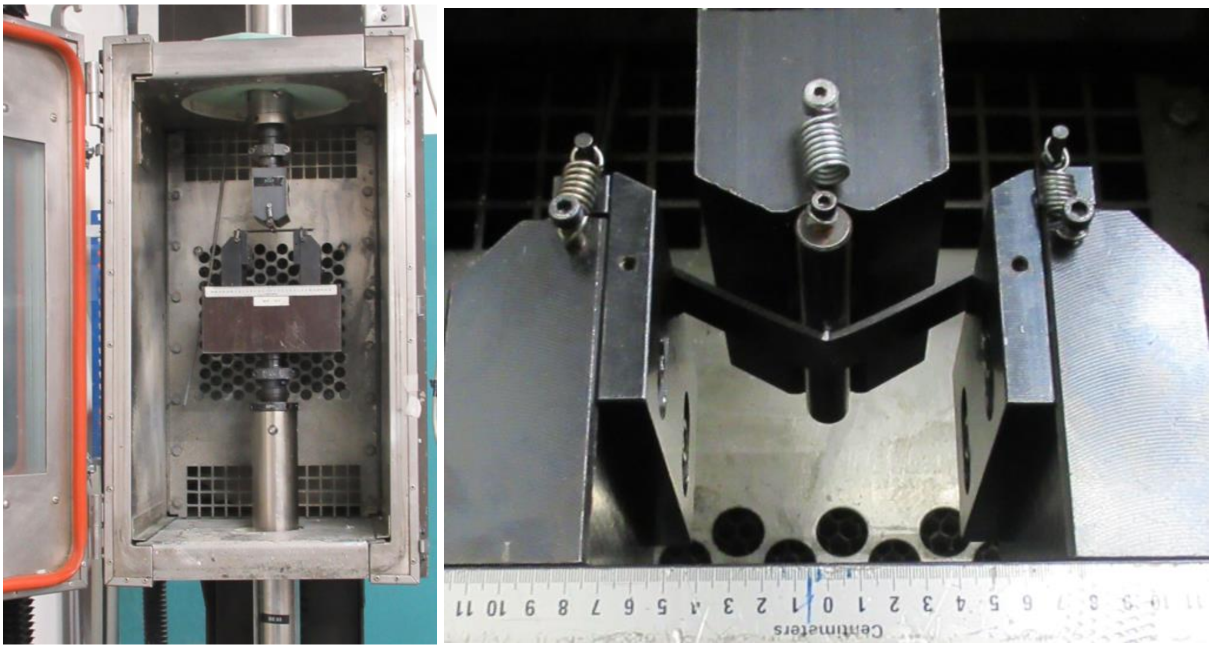


Figure 12. Bending test setup before (left) and after (right) test execution.

Five different configurations of the SMA/PA6-CF were tested and compared, concretely:

- Reference PA6-CF material (baseline for comparison).
- Material with 200 µm wires and 3 mm spacing between them, placed at the top.
- Material with 200 µm wires and 5 mm spacing between them, placed at the top.
- Material with 200 µm wires and 8 mm spacing between them, placed at the top.
- SMA integrated composite → 200 µm wires placed in the middle of the thickness.

The results of the bending tests at room temperature are presented in Figure 13 and Figure 14.

Figure 13. Examples of coupons after bending tests at RT. Left: variothermal process. Right: 3 mm spaced wires, placed at the top.

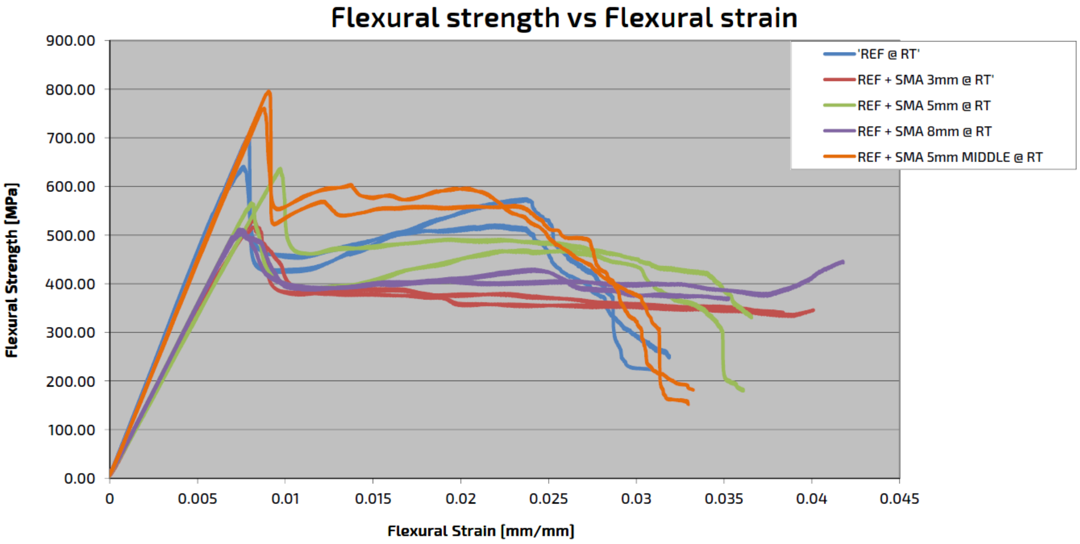


Figure 14. Stress-strain curves of the SMA/PA6-CF coupons tested at RT (all configurations).

There are two major remarks to be made, according to these results. First of all, there is not a noticeable difference in performance between the different variants of the top-placed wires, therefore the selection of the spacing would depend exclusively on the adaptive effect to be achieved thanks to the wires, but not on the resulting mechanical performance of the material. Also, all these configurations entail a moderate loss in the Young modulus compared to the reference, feature that must be taken into account in the design process. Secondly, the coupons manufactured applying the variothermal process show the best performance in terms of yield stress and failure stress of all configurations tested (including reference material), without any loss of Young modulus or failure strain compared to the reference. This result is coherent with the superior bonding between the SMA wires and the polyamide matrix expected in this manufacturing process.

The results of the bending tests at high temperature (100°C) are presented in Figure 15 and Figure 16.

Figure 15. Examples of coupons after bending tests at 100°C. Left: variothermal process. Right: 3 mm spaced wires, placed at the top.

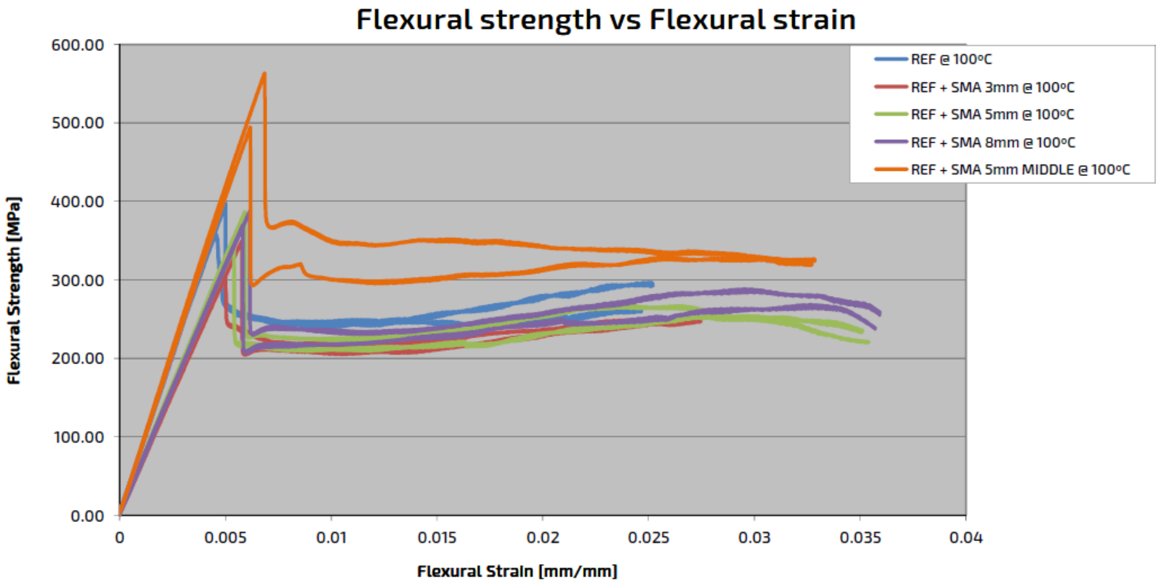


Figure 16. Stress-strain curves of the SMA/PA6-CF coupons tested at 100°C (all configurations).

The results obtained at high temperature are consistent with the observations made at room temperature, showing an enhanced performance of the SMA/PA6-CF when manufactured applying the variothermal process at all temperatures. Again, no remarkable differences are observed among the configurations in which the wires are placed at the top.

3.3 HYBRID MATERIALS

Hybrid multi-material solutions often involve combining different materials or coatings to achieve desired properties or functionalities. Surface pre-treatment is a critical step in ensuring a strong and durable bond between these materials or coatings. The surface pre-treatment methods considered by **FRA** for optimization the bonding quality are:

- sand blasting (surface profiling)
- sand blasting (surface profiling) + primer – PP-MAH foil (coating)
- sand blasting (surface profiling) + primer – Vestamelt powder (coating)

Use of primer enhances bonding of metals with composites. A foil made of a maleic anhydride functionalized polymers (PP-MAH) from **tPE** and Vestamelt Hylink® powder from Evonik were considered as primers to increase adhesion between composite and metal. PP-MAH primer foil was fixed with the CFRP Stacks, whereas Vestamelt was coated onto the Aluminum plates separately (see Figure 17)

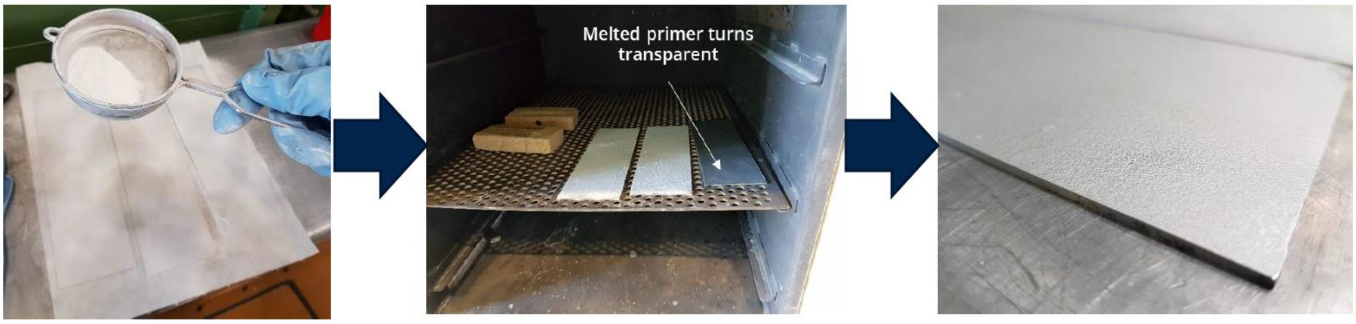


Figure 17. Steps for coating Vestamelt Hylink onto Aluminum plates (left to right): Even distribution of primer on metallic surface; Heating in oven; Coated Aluminum plate

The hybrid laminates without primer and with PP-MAH primer were consolidated in a hot press process. A steel press die with a size of 270 mm x 270 mm was used for this purpose. First, a release film was laid in the tool to ensure easy release of laminates. This was followed by CFRP stacks and aluminum plates. In a 30 minutes cycle, the laminates were heated up to 250°C and gradually consolidated under pressure of around 50 bar (see Figure 18).

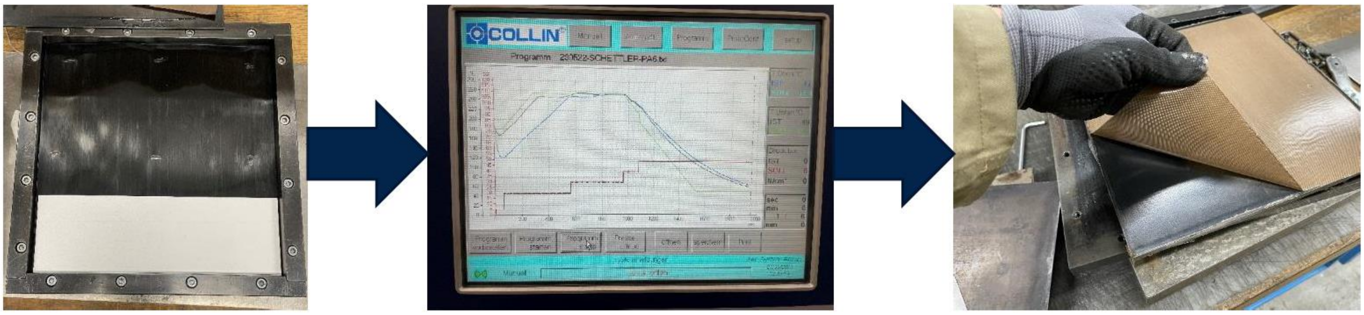


Figure 18. Preparation of laminates with hot press

After production of hybrid laminates, a preliminary assessment was carried out to inspect the quality of hybrid laminates. A simple manual peel-off test showed that there was no bonding effect between metal and composite in absence of a primer (surface was only sand blasted). In contrast, the hybrid plates with PP-MAH primer showed better bonding. However, aluminum and CFRP could be separated easily with hand (see Figure 19), and it was concluded that no further testing might be required to assess their shear properties.

Figure 19. Hybrid laminates: without primer (left); with PP-MAH primer (right)

As a result of the poor results obtained when bonding the two types of material, a more complicated primer (Vestamelt Hylink®) was used. It must be applied in powder form on the aluminum plates. This is followed by the pressing process described above. As a result, a good bond was achieved, which could already be seen from the curvature of the hybrid plate (see Figure 20). This is caused by the different coefficients of thermal expansion. The optimized bond strength of adhesively bonded Al and CFRP was presented in D3.3.

Figure 20. Hybrid laminates: result with the Vestamelt Hylink® Primer

4.ALIGNMENT WITH WP2 DESIGN CRITERIA

The production and application of materials in the industry in general, and in the automotive world in particular, entail the analysis of the complex interrelationships that exist among raw materials, production technologies, material structures and properties, as well as the final component specifications (1).

In SALIENT, the materials are not just an input to be introduced into the designer's calculation, but a key part of the FES design problem. Therefore, all material developments and optimizations done have taken into account the feasibility of the manufacturing processes to which they will be subjected in order to get the designed FES components. It is worth mentioning that, for a certain component, the material-process interactions are bidirectional. This means that the specification of component geometry will restrict the choice of materials and manufacturing processes; and on the other hand the availability of a manufacturing process will also limit the materials that can be employed and also the shapes that can be produced (2). Thus, like in the Ashby's model (3), in SALIENT the interactions among function, material, process and shape (Figure 21) were considered as the central problem from a materials selection and optimization perspective in the FES design that is done within WP2.

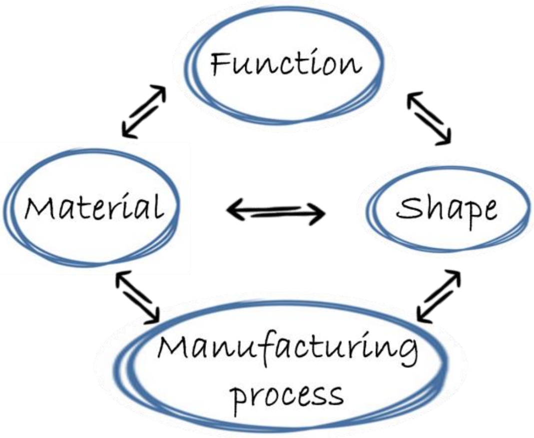


Figure 21: Material-process-shape-function relationship.

In practice, there is a limit within SALIENT in what concerns the number of processes that are within the project partners' reach. This fact has been considered since the very beginning of the design activities (WP2) and has allowed setting clear requirements for the materials developed in this project, thanks to the close interaction existing between both Work Packages (Figure 22).

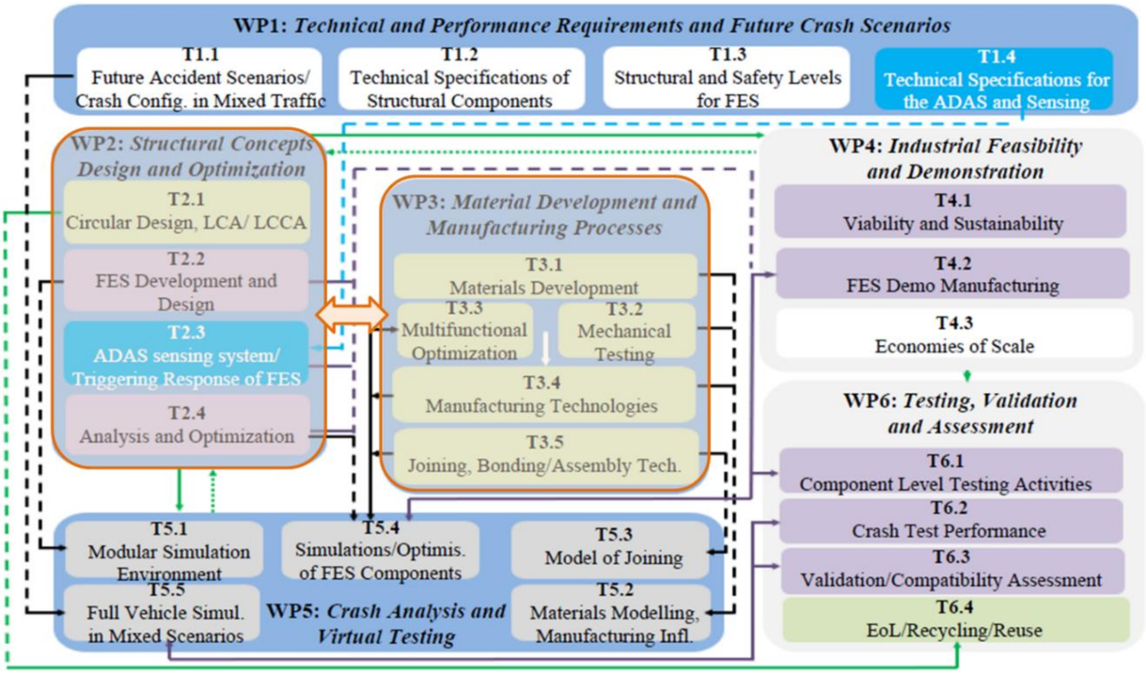


Figure 22: PERT diagram of the technical Work Packages of SALIENT.

Specifically, the high-level design objectives set by WP2 that have guided the optimization of the materials described in this deliverable are:

1. <u>Enhanced crash performance</u>: all material optimizations must have the clear target of improving the crash performance of the materials in different crash scenarios, maximizing energy absorption as required by each FES component. Superior

performance to existing components is targeted while maintaining long-term durability and structural integrity.

2. Lightweight: the development of novel, optimized materials such as the light metal alloys and composites targeted in SALIENT enable the reduction of the overall FES weight, therefore contributing to producing lighter (= less pollutant in combustion engine vehicles, or greater range in Electric Vehicles) and more competitive vehicles.
3. Circular design: the ecological footprint of the materials is an essential criterion that may influence optimization strategies. Design for Recycling (DFR) is a major topic within SALIENT, so it will be ensured that any material, either individually or in combination with others (depending on the requirements to be met for each component), can be recycled in a safe and effective manner.
4. Cost-effectiveness: the optimization of the material must not have a severe impact in terms of costs.
5. Scalability: the optimization must also focus on allowing the increase in the production rate of the materials, to enable potential economies of scale in the future and cover any market needs.

Also, the feedback provided by T3.2 on the characterization results has driven the optimization approach for each material.

5. MULTI-LEVEL, MULTI-FUNCTIONALITY ASPECTS OF THE OPTIMIZATION OF THE MATERIALS

The necessity of the combining the constituents of base for building the microstructure of the materials, is lot more evidence into the composite materials as the fibers reinforced polymeric composites. The multi-functional optimizing of the microstructure of a composite material, must be focused on achieving the desired combination of properties and functions of the material among the single constituents (matrix, reinforced fibers, added fillers, matrix additives, functionalization of the matrix/fibers interface, and so) on while minimizing trade-offs. Different optimization techniques and methods can be used for optimization the microstructure of the materials.

The first step is realizing a micromechanics model of the material and related simulations (virtual characterization) through analytical methods, finite element analysis (FEA), molecular dynamics (MD), density functional theory (DFT), and Monte Carlo simulations. With these techniques is possible to model and predict the behaviour of materials at different scales (atomic, nano, or macro scale). With these models it's possible to understand the structure-property relationships, simulate material responses under different conditions, considering the effects of the manufacturing process (see the deliverable D3.5) of the final components. with micromechanics model and virtual characterization activities. Therefore, it's possible realize a property synergy in which the different properties of the material complement and enhance each other, enabling the material to perform multiple functions simultaneously without compromising overall performance. In addition, these models help selecting and fine-tuning the processing parameters of the manufacturing process (see the deliverable D3.5).

The second step is the identification of optimal material compositions and processing conditions by analysing datasets of several dimensions and complex relationships. In a micromechanics model the optimization involves adjusting factors such as type of the constituents, phase distribution, type of fillers and size, doping levels, type of fibers/matrix interface, etc. This second step can be developed through several technique as:

Design of experiments (DoE): DoE is a statistical approach used to explore the parameter space and identify optimal combinations of factors affecting material properties by systematically varying input parameters and measuring the corresponding outputs.

Multi-objective optimization: These techniques aim to find the best trade-off solutions between conflicting objectives. These methods consider multiple performance criteria simultaneously and identify the Pareto-optimal solutions, which represent the optimal compromises between different properties. Evolutionary algorithms, genetic algorithms, and gradient-based optimization methods are commonly used in multi-objective optimization.

Topology optimization: Topology optimization is used to determine the optimal distribution of material within a given design space to achieve desired properties. By iteratively redistributing material or void, this method optimizes the material layout to maximize performance while satisfying specified constraints.

Machine learning and data-driven approaches: Machine learning techniques, can be used to analyse and predict material properties based on available data. These methods learn patterns and correlations from existing experimental or computational data and can assist in guiding the optimization process. This algorithm act on integrated materials databases in which we find data on materials properties, structures, processing conditions, and performance. These databases, provide a valuable resource for material design and optimization by enabling the identification of trends, correlations, and potential design strategies.

Additive manufacturing and 3D printing: Additive manufacturing techniques, offer unique opportunities for material design and optimization. With the ability to fabricate complex geometries and tailored structures, additive manufacturing allows for the creation of multi-functional materials with precise control over composition, microstructure, and performance.

6. CIRCULAR, LIGHTER AND SAFER MATERIALS

According to the objectives of the SALIENT project, as stated in the GA, the focus is, among other things, on the development of an innovative and circular design concept for the vehicle's FES. For this reason, the project places a strong emphasis on the development of fibre-reinforced thermoplastics. Thermoplastics are environmentally sustainable for many reasons. Thermoplastics are 100% recyclable. They can be completely recycled by simple mechanical shredding in an energy-saving manner. The recycled material can be used as a raw material to make new products. Thermoplastics saves resources like no other material. The use of thermoplastics helps to saves valuable resources in a number of ways, for example in the automotive industry by reducing fuel consumption through lightweight design. In addition, the production of thermoplastics requires significantly less energy than, for example, the production of glass, ceramics or aluminium. These sustainability aspects, together with the material optimisation described in D3.4, results in the innovative and circular materials required for a sustainable FES design. To further increase this lightweight potential, the developments described for SMA and hybrid materials are used, particularly where high ductility, strength, stiffness and energy absorption are required.

7. CONLUSIONS

In this project task, a multi-level, multi-functional optimization approach is being developed for novel materials. This approach aims to enhance various attributes of these materials, including strength, stiffness, geometry, anti-static properties, acoustic performance, and thermal resistance. A collaborative effort involving **UNN**, **tPE**, and **FRA** is dedicated to analysing the impact of process-induced microstructures on damage evolution under diverse loading conditions. The work is focused on optimizing the performance, damage tolerance, and lightweighting of composite materials. Additionally, **CID** is responsible for ensuring that the optimization aligns with the design criteria of Work Package 2 (WP2). This alignment is crucial for achieving the project's objectives. Furthermore, **CRF**'s research focuses on exploring the multi-functionality aspects of the optimization, which will contribute to the comprehensive understanding and application of these novel materials.

Within the scope of the task, extensive tests were carried out to optimise the TP CFRP developed in Task 3.1. A multi-level optimisation of the composite material was carried out, which investigated possibilities for optimisation from the matrix to the laminate structure. The aim of the investigation was to increase the ductility of the FRP and thus improve the energy absorption. This made it possible to improve the use of TP CFRP in FES and other crash-relevant components. Very good results were achieved in terms of increasing the strength and ductility of the material through matrix as well as structural modifications. In particular, the crack-stopper layer has a positive impact on the damage evolution, strength and energy absorption. Consequently, these materials can be applied in the design of FES, promoting its lightweight and sustainable features. The hybrid materials developed in T3.1 were optimised with regard to the optimised adhesion of plastic and aluminium, providing an ideal composite material for use in FES. The adaptation according to the WP2 design criteria was considered and monitored in the development process.

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