FIBRECHAIN: CHARACTERISATION AND MODELING OF THERMOPLASTIC COMPOSITES PROCESSING

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ABSTRACT *Thermoplastic composites feature the advantage of melting and shaping. The material properties during processing and the final product properties are to a large extent determined by the thermal history of the material. The approach in the FP7-project FibreChain for process chain modeling of thermoplastic composites is presented.*

INTRODUCTION

One of the main advantages of thermoplastic composites is the possibility of melting and shaping. Based on semi-finished products like consolidated laminates and prepreg tapes, parts can be produced using press forming or tape placement technology. During preceding steps like prepregging and press consolidation, and during subsequent processes like trimming and joining the material is repeatedly heated and cooled down. Next to a direct influence on the shaping production steps the thermal history may also influence the final product properties in terms of e.g. strength and chemical resistance.

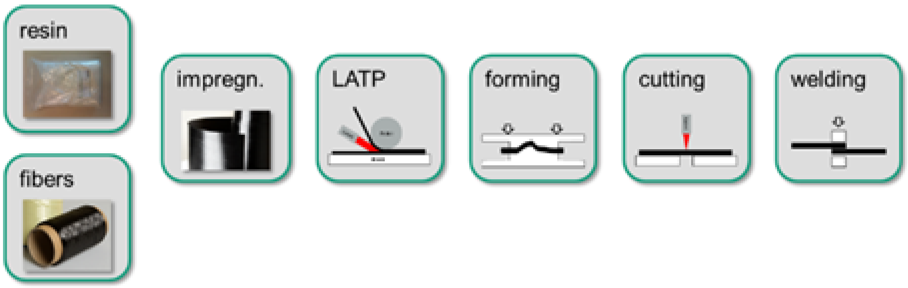

Figure 1. Example process chain for thermoplastic composites processing

As a consequence, this observation leads to the conclusion that for a sound prediction of the production processes and the final properties the incorporation of the temperature is needed. In the case of press forming the influence of heating and cooling down of the composite is considered low compared to fast processes as laser assisted tape placement, where typical heating and cooling rates above 1000 K/s occur. The temperature history results in thermal stresses that on their turn can result in geometric deviations and diminished mechanical properties. Furthermore, the degree of crystallinity of semi-crystalline resins, of direct influence on mechanical properties and chemical resistance, may be changed. The approach to incorporate the process chain for modeling of thermoplastic composites, as considered in the FP7-project with the acronym FibreChain (www.fibrechain.eu), is presented and illustrated on the basis of selected examples.

THERMOPLASTIC COMPOSITES

In thermoplastic composites the advantages of stiff fibers are combined with the advantages of a ductile thermoplastic matrix. As in their thermoset counterparts different architectures are available, from woven fabric, to non-crimp fabric to unidirectional (UD) tapes. One of the main advantages of thermoplastics is the possibility of melt shaping to obtain the final product which yields a potential for fast and automated processing for large series production. This involves forming as well as joining of parts to assemblies. Furthermore end-of-life and production scrap can be re-used.

Thermoplastic composites generally feature a higher toughness than thermoset composites which makes them suitable for crash applications. UD-tapes are gaining popularity not only because of the excellent mechanical properties in fiber direction, but also since tape placement processes are getting more mature. While for short fiber reinforced thermoplastic extensive knowledge on processing and optimization of product performance has been developed, this is still not the case for long and continuous fiber composites.

In this research the focus is on continuous fiber composites, which feature the largest potential for weigh savings. Different material combinations are considered in which different fibers are combined with a number of thermoplastic resins. The semi-crystalline resin PA12 is gaining popularity in oil & gas industry and currently in the automotive industry as well. PEEK is well-known in high-end applications in aerospace and medical industry. In contrast to both aforementioned polymers PES is an amorphous polymer which completes the test-matrix. As fibers carbon AS4 and T700 are taken into account in woven fabric as well as in UD. In some special cases also s-glass is considered for comparisons.

THERMOPLASTIC COMPOSITES PROCESSING

One of the main advantages of thermoplastic composites is the relative ease of processing which enables low cycle times, especially suited for automated mass production. While autoclave technology is still the reference in aerospace industry, the automotive industry is exploring fast and cost-efficient processing technologies especially in the field of press forming, tape placement and winding and joining processes.

During subsequent processing changes will inevitably occur in the material. Next to the wanted geometry changes unwanted geometrical effects can occur as well. These defects can be attributed to the inherent properties of the material, to inherited inaccuracies of the predecessor material and/or can be process related. The strong anisotropy related to the architecture of the stiff fibers in a polymer matrix may cause wrinkling in the case of severe shearing. An example of inherited inaccuracies can be poor tape quality in the case of tape placement or winding, which may results in a poor interface or inhomogeneous distribution of fibers. Process related defects can occur due to low pressures during forming, low pre-tension or too low or high temperatures in tape placement.

Figure 2 shows the development of crystallinity of AS4/PA12 from the neat resin to the tape-placed and press-consolidated laminates.

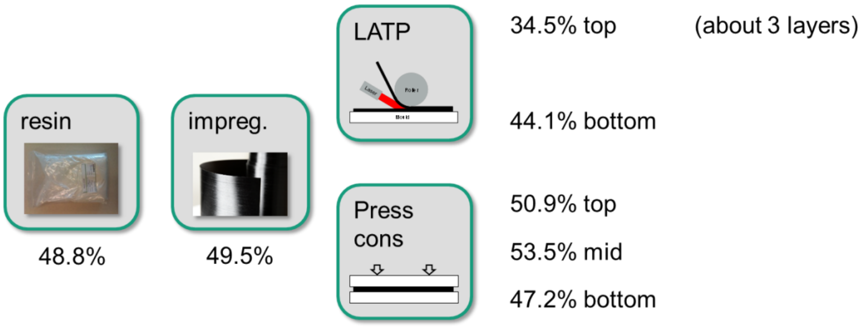

Figure 2. Degree of crystallinity for PA12 in four steps of a process chain (enthalpy of fusion ΔH = 134 J/g)

The degree of crystallinity was measured using DSC equipment with a fusion enthalpy for 100% crystalline PA12 of 134 J/g [1]. The degree of crystallinity for the neat resin was identified to be about 49%. After the impregnation process the tape shows about the same value. This means that cooling is slow enough in order to obtain a high crystallinity again. If the pre-preg tape is used in press-consolidation, which is known to be a slow process with moderate heating and cooling rates, hardly any difference is observed. However, there might be a trend that the center layers have a higher degree of crystallinity than the outer layers which have thermal contact to the tools. This means the cooling rate at the surface will be higher than in the center at all times. In laser tape placement, which is in contrast to press-consolidation a very fast process, a large difference between the top and bottom layers is observed. The average of the three top plies shows a value of about 35%. It is expected that the top layer even has a lower crystallinity since this is the last layer to be deposited and cooled down very rapidly (~1000 K/s). All other layers have been subjected to more heating and cooling cycles with lower rates such that growth of spherulites could still take place. However, even for the first layers the level of the neat resin is not obtained anymore. During press forming the cycle times are much lower than in press consolidation, such that change of crystallinity is likely to occur. However, especially the fast laser tape placement process negatively influences the degree of crystallinity.

MODELING APPROACH

One of the aims of the project is the development of sufficiently accurate simulation models for the subsequent steps in the process chain. This means that the properties that are changed during the processing steps and that are relevant for the final product performance are to be simulated accurately. These properties are for instance the fiber orientation and thickness changes of the semi-finished and final products. Furthermore the resin properties change due to the temperature changes in the process chain. Typically the thermoplastic composites process chain consists of steps in which the resin is repeatedly melted and solidified. As shown in the previous section this causes changes in crystallinity in different parts of the final product which at its turn might influence the product performance. It is therefore inevitable to incorporate the thermal history in the process chain, which is one of the main challenges in the project.

Three processes are taken into account extensively; press forming, laser assisted tape placement and laser cutting. For the first two processes clearly the objective is the design of a next generation of predictive software to be used in industry to support the development of process windows. Once the thermal history is fully known Avrami-type of crystallinity models are used to predict the degree of crystallinity in different areas of the part [2]. In the simulation of laser cutting the focus is on the understanding of the different mechanisms, e.g. conductivity of fibers and matrix, and degradation behavior.

Press forming

The simulation of the press forming process is to current time usually performed in an isothermal fashion. AniForm is the software of choice in this project since this software has proven its ability to simulate thermoplastic composites forming with different architectures at melt temperatures. AniForm is an implicit 3D finite element code for modeling large deformations of highly anisotropic materials [3]. The simulation accuracy for these strongly depends on an accurate prediction of the fiber angles. Therefore the software features an appropriate decomposition of the deformation gradient and an accurate material update scheme.

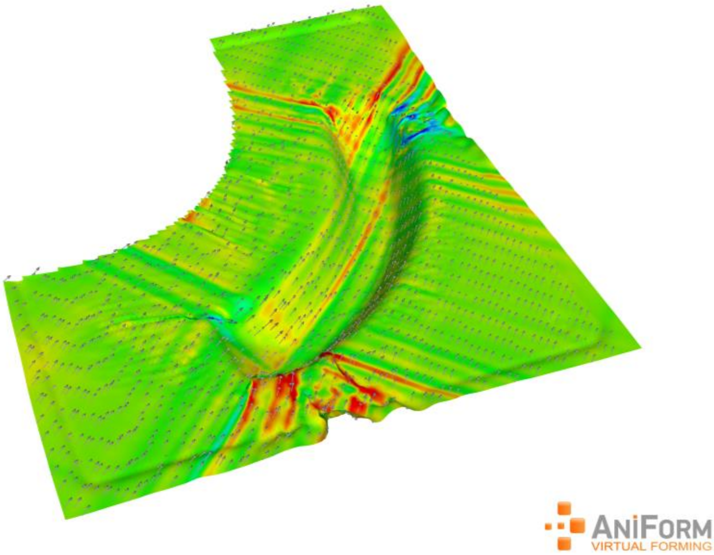

Figure 3. Simulation of a control arm showing the predicted fiber orientations and shear angles

Apart from fiber orientation the temperature history has to be modeled. Two approaches will be followed: 1. Integration of thermal equilibrium in the AniForm software and 2. Conduct a staggered approach in which the mechanical and thermal equilibrium are solved sequentially. In the latter case the thermal equilibrium can be solved using a general purpose software, e.g. Ansys. The obtained temperature distribution is transferred to AniForm for the mechanical step considering the temperature dependency of the material parameters. Subsequently the updated geometry obtained from AniForm is transferred to Ansys for the next thermal load step. In order to do so the material behaviour has to be characterized in melt conditions over a wide temperature range. This has been addressed previously by Haanappel at al. who gives an overview of the tests needed to characterize inter-ply friction, intra-ply shear and bending [4][5].

Laser assisted tape placement

For laser assisted tape placement the aim is to provide a model in which the temperature field is calculated for a given material depending on the process conditions, as there are placement velocity, laser power and laser angle, or in an advanced settings possibly pre-heating and cooling. The modeling of the transient temperature field during the tape placement process is performed in two different ways. Following the approach of Grouve [6], the problem is reduced to a 1½-dimensional problem in which the in-plane conductivity is neglected. The through-thickness heat conductivity is taken into account using a collocation scheme. However, in order to improve the accuracy of the model by considering the in-plane conductivity in the tape and laminate a full 3D approach is necessary.

To study and optimize the laser assisted tape placement process a 3D process model has been developed in the commercial code Ansys-Workbench. The CFD and design optimization modules of Ansys were used in this model. The laser heat input is calculated with an optical ray tracing model developed by Grouve [6]. Anisotropic, temperature dependent material parameters were used in the simulations. The average temperature at the nip point and the cooling rates are the key output parameters which determine the bond strength and crystallinity of the product, whereas the design process parameters are the process speed, laser power and laser angle.

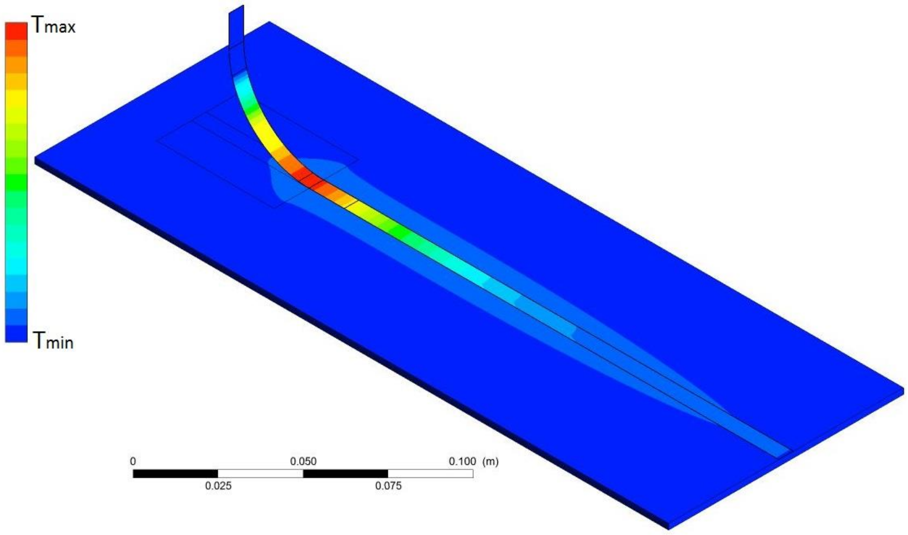

Figure 4. Simulated steady state temperature distribution for laser assisted tape placement of C/PA12

Figure 4 shows a typical calculated temperature field in the steady state situation for tape placement of C/PA12. The maximum temperatures are in the ideal case obtained in the nip point between tape and substrate. It can be recognized that the substrate heats up due to in-plane conductivity in the area next to the tape. However, the in-plane conductivity in the tape in tape direction was identified to be much more important for the development of the temperature field. It is easy to understand that at low welding speeds the in-plane conductivity gets more dominant. By variation of the placing velocity and the laser power and angle, the nip point temperature can be optimized using response surface modeling, see Figure 5.

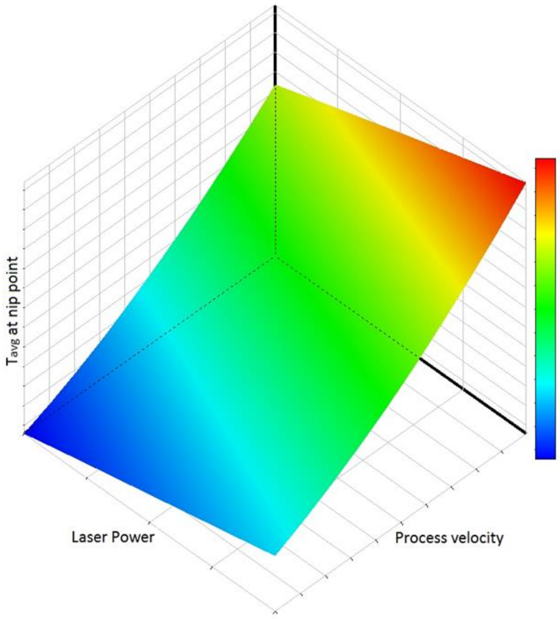

Figure 5. Response surface for the average temperature at the nip point

In future the 3D heat input of the considered laser heating system is modeled using laser beam propagation models developed by Fraunhofer Institute for Laser Technology ILT.

Laser Cutting

During processing of thermoplastic composites usually semi-finished products like pre-consolidated laminates are used, which are subsequently processed to give the desired product shape. One important processing step is the milling or cutting of the blanks or the final product. Laser cutting is one of the methods that allow for high processing speeds, however the high temperatures can result in a zone near the cut with different properties, the so-called heat affected zone (HAZ). Two dimensional numerical simulations are performed with the commercial code Ansys, using the element birth and death feature in the mechanical module. To realize the progress of laser cut in the simulation, scripting has been performed using Ansys APDL. Using this model, the cutting process parameters can be optimized to reduce the size of the HAZ.

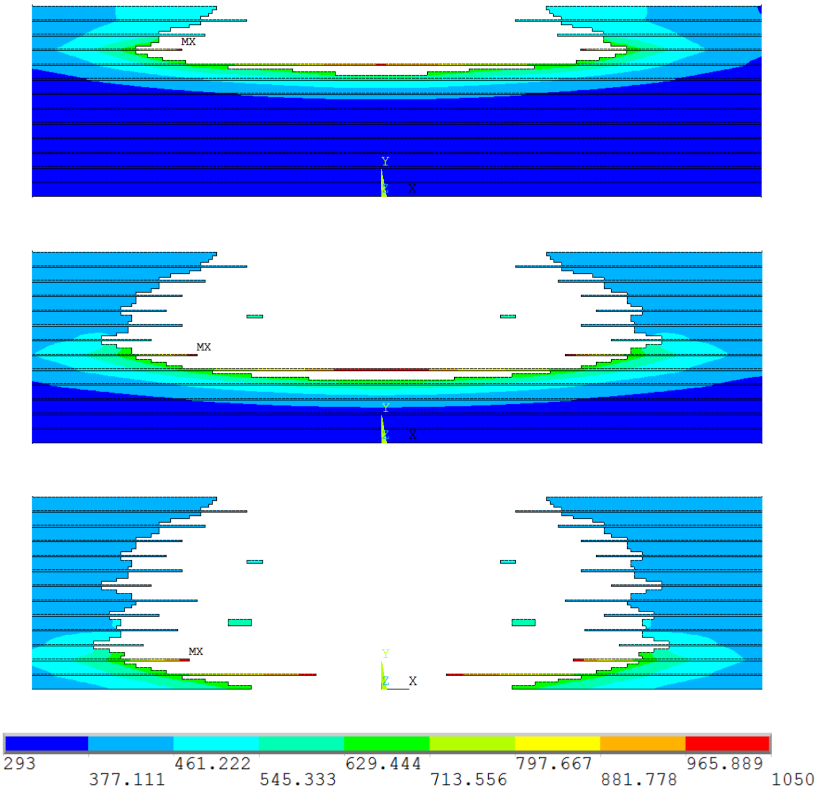

Figure 6. Simulated temperature in different phases of the 2D numerical simulation of laser cutting for C/PA12

Different stages of the cutting simulation of C/PA12 are shown in Figure 6. In the model a small number of carbon fibers are embedded in a PA12 matrix. Laser heat is supplied from the top side and elements are deleted when the degradation temperatures of resin and fiber are reached. Since the carbon fibers are very good heat conductors, the resin tends to degrade along the fibers, resulting in clean fibers at the cutting edge which is also seen in laser cutting experiments. The model support the understanding of laser cutting processes and the influence on the materials, however some efforts are needed to make the simulation more representative for practical situations.

CONCLUSIONS

One part in the FP7-project with the acronym FibreChain focuses on the simulation of the complete thermoplastic composites process chain in order to predict and optimize the final product performance. In this paper, which basically gives an overview on the activities within this project part, it was shown that an accurate incorporation of the thermal history is essential for reaching this aim. The modeling approach has been discussed on the basis of the press forming, laser assisted tape placement and laser cutting process. In the remainder of the project the models will be further validated on the basis of experimental results and the whole numerical process chain will be shown for a demonstrator.

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