



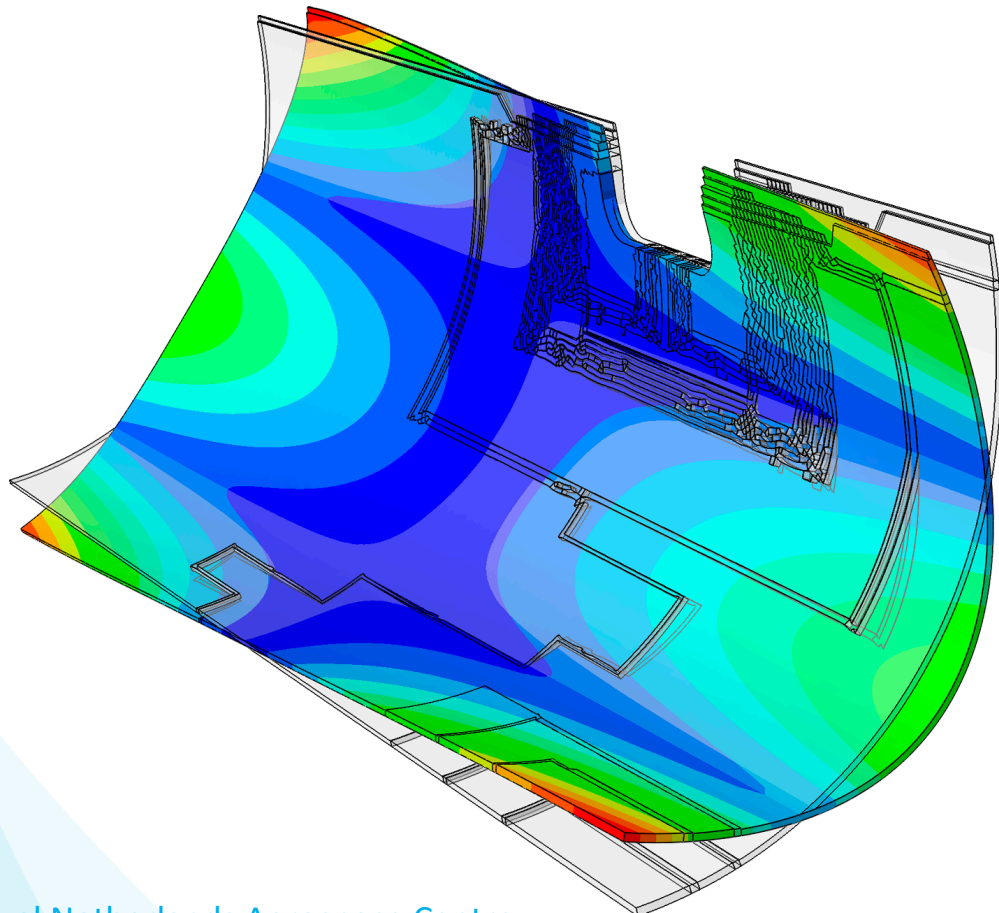
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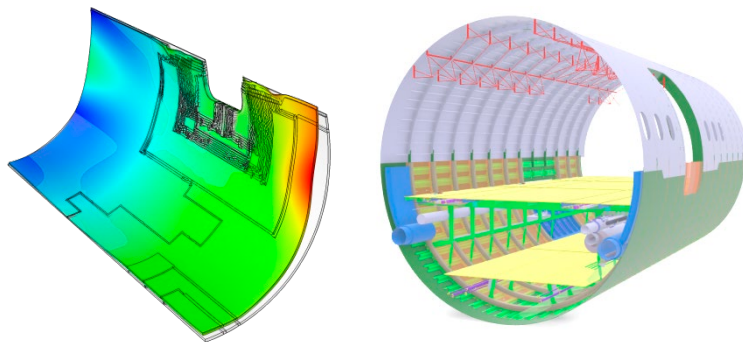
Large carbon fibre reinforced thermoplastic fuselage manufacturing supported by virtual processing

CUSTOMER: JU Clean Sky



NLR – Royal Netherlands Aerospace Centre

Large carbon fibre reinforced thermoplastic fuselage manufacturing supported by virtual processing



(left) Distortion prediction (scaled) of a part of the thermoplastic fuselage skin and (right) the total fuselage assembly

Problem area

To reduce the emissions of aircraft the next generation fuselage structure concepts are needed in which cabin, cargo and physical system elements are integrated. In the Platform 2 of the Large Passenger Aircraft (LPA) IADP of Clean Sky 2 led by Airbus the aim is to develop demonstrators of such concepts, including a full scale 8.5 meter section of a fuselage. The lower fuselage section is a 180° full scale multi-functional integrated thermoplastic fuselage shell, incl. cabin and cargo floor structure and relevant main interior and system elements. Advanced design principles, innovative system architecture, advanced materials and processes to generate high potential solutions for next generation fuselages are used.

Description of work

In this technical report the distortion analysis of the composite skin and a multi-purpose (rate-type, thermal, crystallinity, residual stress) material model will be presented. This is applied to the lower skin of the large demonstrator (length 8.5 m, diameter about 4 m). The lower skin will be manufactured by NLR.

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With this material processing model the behaviour during manufacturing and assembly steps such as fibre placement, consolidation, and welding is predicted. The aim of this work is to create a physics based finite element method (FEM) material model to capture thermomechanical effects. This includes prediction of mechanical effects with temperature variations, residual stresses and distortion of the composite structure such as the skin and stringers. Development and testing of Abaqus thermal subroutines (crystallinity, melt physics, cooling) and mechanical material subroutines has been done and results will be presented in this contribution.

Results and conclusions

It can be concluded that the virtual processing models give valuable insight in the manufacturing process and allows for improvement of the actual manufacturing. The material is calibrated using DSC data for the LM-PAEK material which is used for prediction of temperatures and crystallinity during the processing steps, e.g. fibre placement, welding, consolidation. It shows that due to the processing conditions the final crystallinity does vary considerably. Due to lack of mechanical process material data a simplified approach is used on a higher level for (trend) prediction of the residual stress and distortion in parts of the fuselage skin after fibre placement. This shows that distortion is present however because of the flexibility of the part this can be removed with a small force applied.

Applicability

The methods and results from this research can be widely applied to other thermoplastic materials and manufacturing processes. This would require a new characterization of the material used.

GENERAL NOTE

This report is based on a presentation held at the RaeS Aircraft Structural Design Conference at 8 October 2020.

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Summary

To reduce the emissions of aircraft the next generation fuselage structure concepts are needed in which cabin, cargo and physical system elements are integrated. In the Platform 2 of the Large Passenger Aircraft IADP of Clean Sky 2 the aim is to develop demonstrators of such concepts, including a full scale 8.5 meter section of a fuselage. The lower fuselage section is a 180° full scale multi-functional integrated thermoplastic fuselage shell, incl. cabin and cargo floor structure and relevant main interior and system elements, see Figure 1. The lower fuselage is developed and manufactured by the STUNNING consortium, led by GKN-Fokker. Advanced design principles, innovative system architecture, advanced materials and processes to generate high potential solutions for next generation fuselages are used [1].

The significant weight reduction resulting from this integrated approach, based on advanced thermoplastic manufacturing and assembly principles, will contribute to the environmental challenge to reduce the emissions while enhancing the effective space for passengers and cargo. Manufacturing costs and assembly times will be reduced and production rates will be increased. However the manufacturing of such a large thermoplastic part is challenging so therefore the support of virtual processing tools is essential. In this contribution the distortion analysis of the composite skin and a multi-purpose (rate-type, thermal, crystallinity, residual stress) material model will be presented. This is applied to the lower skin of the large demonstrator (length 8.5 m, diameter about 4 m). The lower skin will be manufactured by NLR.

With this material processing model the behaviour during manufacturing and assembly steps such as fibre placement, consolidation, and welding is predicted. The aim of this work is to create a physics based finite element method (FEM) material model to capture thermomechanical effects. This includes prediction of mechanical effects with temperature variations, residual stresses and distortion of the composite structure such as the skin and stringers. Development and testing of Abaqus thermal subroutines (crystallinity, melt physics, cooling) and mechanical material subroutines has been done and results will be presented in this contribution.

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Abbreviations

ACRONYM	DESCRIPTION
AFP	Automated Fibre Placement
CATIA	CAD software
DSC	Differential Scanning Calorimetry
FE	Finite Element
FEM	Finite Element Method
HETVAL	Abaqus user subroutine
IADP	Innovative Aircraft Demonstrator Platform
LM PAEK	Low Melt Polyaryletherketone
LPA	Large Passenger Aircraft
MFFD	Multi Functional Fuselage Demonstrator
NLR	Royal Netherlands Aerospace Centre
PAX	Passengers (Aircraft)
PEEK	Polyetheretherketone
PEKK	Polyetherketoneketone
STUNNING	SmarT mUlti-fuNctionNal and INtegrated thermoplastic fuselaGe
UEXPAN	Abaqus user subroutine

1 Abstract

To reduce the emissions of aircraft the next generation fuselage structure concepts are needed in which cabin, cargo and physical system elements are integrated. In the Platform 2 of the Large Passenger Aircraft (LPA) IADP of Clean Sky 2 the aim is to develop demonstrators of such concepts, including a full scale 8.5 meter section of a fuselage. The lower fuselage is a 180° full scale multi-functional integrated thermoplastic fuselage shell, incl. cabin and cargo floor structure and relevant main interior and system elements, see Figure 1. The lower fuselage is developed and manufactured by the STUNNING consortium, led by GKN-Fokker. Advanced design principles, innovative system architecture, advanced materials and processes to generate high potential solutions for next generation fuselages are used [1].

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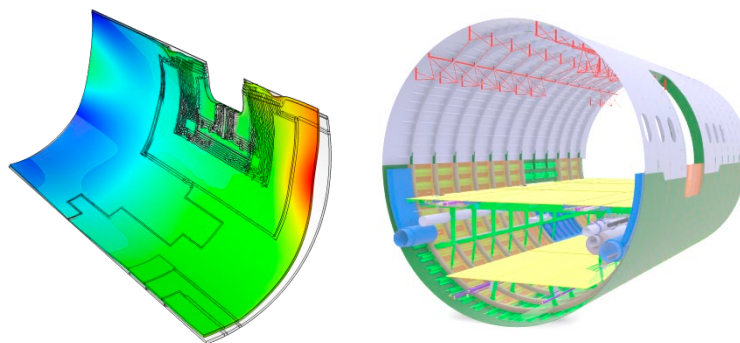


Figure 1: (left) Distortion prediction (scaled) of a part of the thermoplastic fuselage skin and (right) the total fuselage assembly (source: Annex: Clean Sky 11th Call for Proposals – List and Full Description of Topics, 21 November 2019, p. 77)

With this material processing model the behaviour during manufacturing and assembly steps such as fibre placement, consolidation, and welding is predicted. The aim of this work is to create a physics based finite element method (FEM) material model to capture thermomechanical effects. This includes prediction of mechanical effects with temperature variations, residual stresses and distortion of the composite structure such as the skin and stringers. Development and testing of Abaqus thermal subroutines (crystallinity, melt physics, cooling) and mechanical material subroutines has been done and results will be presented in this contribution.

2 Background

Within Clean Sky 2 Large Passenger Aircraft Platform 2, the Multifunctional Fuselage Demonstrator (MFFD) is developed to validate high potential combinations of airframe structures, cabin/cargo, and system elements. The paper focusses on the 180° full scale multi-functional integrated thermoplastic lower fuselage shell structure. This 180° fuselage shell will be the lower part of the MFFD, see Figure 2 [1]. It is developed and manufactured by the STUNNING consortium. The overall objectives of the MFFD are to demonstrate for the next generation fuselage:

- Enable a high production rate of a minimum of 60 aircraft per month
- Achieve a total fuselage weight reduction of 1000 kg
- Achieve a reduction of recurring costs

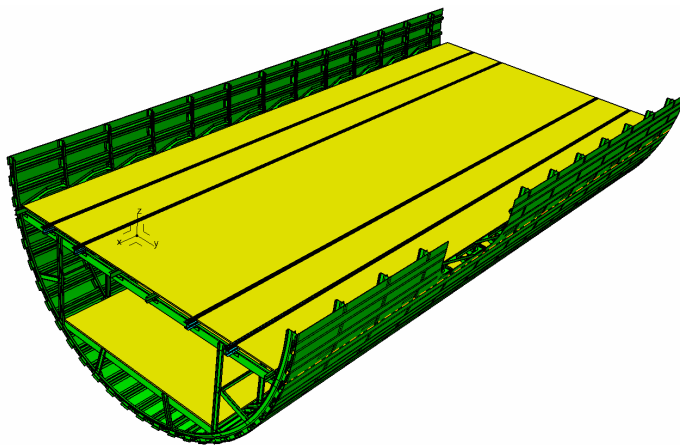


Figure 2: Overview of the multi-functional integrated thermoplastic lower shell of the MFFD, including passenger and cargo floor structures and relevant main interior and system elements (status in the course of 2018; source: Fokker). LPA dissemination (STUNNING)

NLR is responsible for the manufacturing of the thermoplastic skin of the lower fuselage shell and related virtual manufacturing aspects. The aim of this work is to create a physics based finite element thermoplastic material model to perform distortion and crystallinity predictions to support the manufacturing. Process models of composite materials are useful tools for understanding the effect of process parameters and variables on the final part and reducing manufacturing risks and costs. For the skin/shell the high performance carbon fibre thermoplastic LM-PAEK is selected. Due to confidentiality reasons the material properties and results are not published.

Currently commercial tools available for thermoplastic virtual processing predictions are limited and mainly focussed on draping [6]. Common semi-crystalline thermoplastic materials such as PEEK, PEKK, LM-PAEK are visco-elastic and their unrelaxed values of moduli are temperature and crystallinity dependent. Most of the crystallization kinetics models in the literature are valid for constant temperatures or cooling at constant cooling rates. In work by Gordnian and Tierney [2, 5] the PEEK material is investigated and numerical models are developed and calibrated. In interesting work by Audoit in [3] the new LM-PAEK material is investigated using DSC and a comparison is made with PEEK material. Baran [4] presents an overview of processing methods for both thermoset and thermoplastic material. It shows the multi-physics nature of the material during processing which poses challenges for material model inputs and calibration of the models. For the lower shell of the MFFD it is desired to have a rate-type crystallization/melt kinetics model which is independent of the temperature cycle. A rate-type crystallization kinetics model has been

developed in the project in the Abaqus finite element software for prediction of degree of crystallinity during crystallization process [2].

Apart from the prediction of temperatures and crystallinity also the distortion of thermoplastic material is investigated. From previous research it was shown that carbon fibre thermoplastic composites can create considerable residual stresses during processing which can cause distortion during processing or when released from the mould. This is mainly caused by the cooling down of the composite semi-crystalline thermoplastic material from a high temperature, which can be 350 °C or higher. Because of the difference in coefficient of thermal expansion (CTE) in the composite layers, large internal strains and stresses develop.

With this material model that will be integrated in Abaqus finite element analyses using subroutines, the aim is to make predictions on a higher level of the structure such as the skin and stringers.

However similar to thermoset composites it appears to be difficult to obtain reliable material data. Therefore several thermal and mechanical tests have been specified and will be carried out to aid in the further quantification of material properties and understanding of the material behaviour.

3 Methodology

Thermoplastic carbon composites crystallization and residual stress/distortion has been a subject of interest to researchers for many years. Many polymers, when cooled down from molten state, form a semi-crystalline microstructure. Isothermal crystallization kinetics of semi-crystalline polymers is generally investigated using Avrami models. During processing, such as Automated Fibre Placement manufacturing (AFP) and consolidation the thermoplastic composite parts may experience complex temperature cycles. A differential form crystallization kinetics/melt kinetics model, along with an induction time model for prediction of the onset of crystallization is most applicable. Important requirements for the model are:

- Thermal effects prediction
- Residual stress prediction
- Crystallinity prediction
- Distortion prediction

The model developed is based on the work by Gordnian [2] where a differential crystallinity model was developed. The model is calibrated using a large number of DSC tests on the LM-PAEK carbon thermoplastic composite material. The crystallinity factor X_{vc} is calculated using the Avrami equation 1 as basis.

$$X_{vc} = X_{\infty} [1 - e^{-kt^n}] \tag{Eq. 1}$$

Here X_{vc} is the volume fraction of crystalline material, X_{∞} the maximum fraction of crystallinity, k the kinetics constant, t the crystallization time and n the Avrami exponent. This equation was converted to rate dependent crystallinity from which a material model based on subroutines in the finite element software Abaqus was created. The material model consists of a thermal part where the temperature distribution, crystallinity, melt physics and heat generation is calculated. This is interfaced with a mechanical model which uses the thermal model results to calculate the expansion of the material, residual stress and related distortions. An overview of the subroutines is shown in Figure 3.

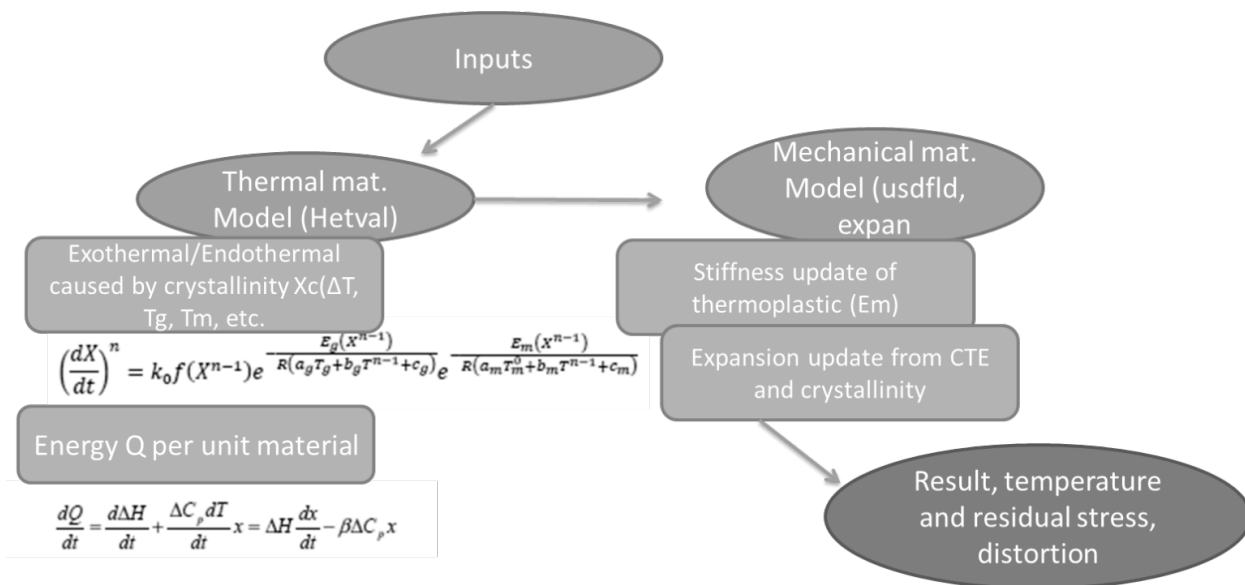


Figure 3: Subroutine overview with the HETVAL and UEXPAN subroutines in Abaqus

Here the main parameters are X_{vc} is the volume fraction of crystalline material, X_{∞} the maximum fraction of crystallinity, k_0 the pre-exponential factor for temperature dependence of crystallization rate, t the crystallization time and n the Avrami exponent. And $a_g, b_g, c_g, a_m, b_m, c_m$ are model constants and $\frac{e_m}{R}$ and $\frac{e_g}{R}$ model parameters for temperature dependence of crystallization rate which need to be defined using a look up table. And Q is the heat input, H the enthalpy, C_p is the heat capacity. The material model is implemented in the form of two Fortran code subroutines [8]. These are integrated in the finite element calculations where per increment the internal values are updated. The subroutines have been evaluated using simple tests.

DSC tests were performed at NLR using the TA instruments Q2000 DSC. The tests were done using a specific Tzero pan and lid containing and heating the sample with a weight of 5 mg, see Figure 4. For a full calibration of the material model DSC data including isothermal and non-isothermal tests is performed.

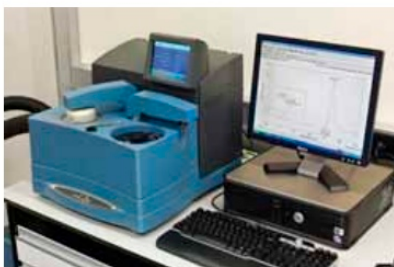


Figure 4: DSC setup used for thermoplastic composite tests

For the isothermal DSC tests temperatures of 250 °C, 260 °C, 265 °C, 270 °C, 275 °C, 280 °C and 290 °C were selected. For the non-isothermal tests a heating and cooling rate of 1 °C/min, 5 °C/min, 10 °C/min, 20 °C/min, 30 °C/min and 60 °C/min were selected. Using the DSC curves the material model subroutines were calibrated.

The method for predicting the residual stress and distortion has been simplified for the results presented. The correlation between crystallinity induced shrinkage of the polymer is difficult to determine with the current material data available. Therefore for the residual stress and distortion predictions the coefficient of thermal expansion of the material is used in combination with the thermal simulation. For future work the crystallinity shrinkage will be included.

4 Results

The presented results in this section are twofold. The previously presented (advanced) material model is tested and calibrated on simple geometries and evaluated against fibre placement and induction welding temperature readings. Another material model that is a simplified thermomechanical model based on expansion coefficients is used for a large fuselage structure demonstrator.

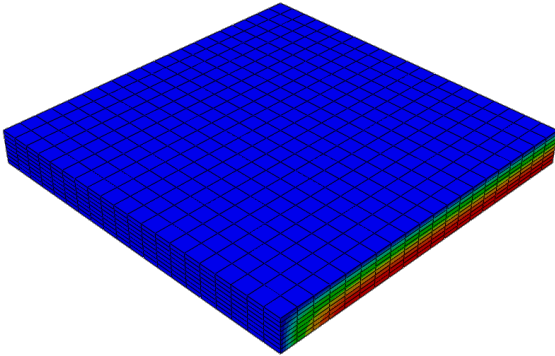


Figure 5: Finite element model used for the material model tests. Temperature boundary conditions are applied on the top surface

From the advanced material model the following trends for thermal and crystallinity results are captured:

- With decreasing temperature, or increasing degree of undercooling, $Tm_0 - T$, the crystallization rate increases
- It is concluded that approaching the glass transition temperature, or decreasing $T - T_g$, decreases the crystallization rate
- High cooldown speeds are needed for lower crystallinity for testing
- Lots of DSC curve fitting is needed

Multiple tests have been done to calibrate the material model onto the DSC data available. Following the calibration of the model the results are shown in Figure 6 where the material is heated up to 350° Celsius and then cooled down with a rapid constant rate of 33° Celsius per second. Due to confidentiality these are not the results for the final LM-PAEK material. Instead the reference data for PEEK from [2] is used.

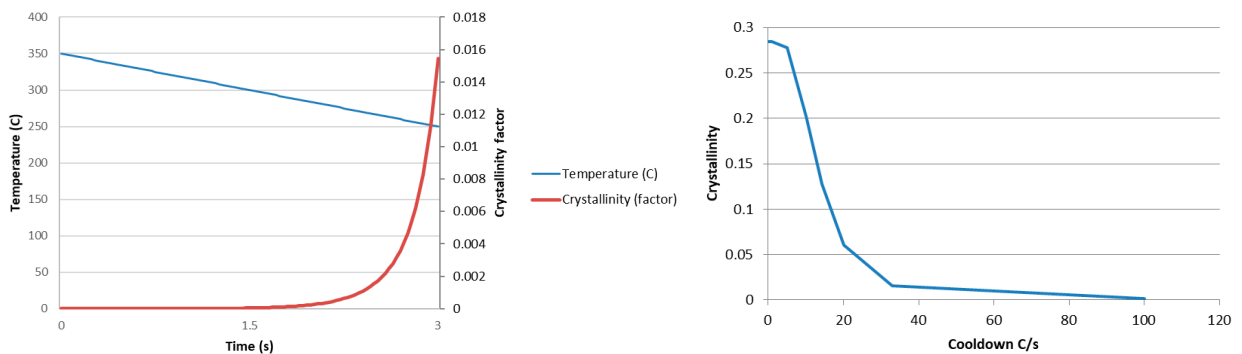


Figure 6: Model results based on PEEK reference material. Diagram of a rapid cooldown from 350°C to 250°C in 3 seconds (cooldown rate of 33° Celsius per second) with in blue the temperature. It can be observed that the red line for crystallinity factor increases up to around 1.8%. On the right the cooldown rate dependent results for the crystallinity are shown when cooled down to room temperature

The figure on the left shows the temperature drop and the slight increase in crystallinity. This aligns with the figure on the right where the rate dependence is shown. The rate dependence is clearly present where a maximum crystallinity is achieved with low cooldown rate (e.g. consolidation). A low crystallinity is achieved with high cooldown rates as the results in the right figure also show. This also aligns with literature findings.

Following is a more realistic temperature variation/multiple cycles are applied to the material using the material model, see Figure 7. Here the melting model is also shown where consequently the crystallinity decreases.

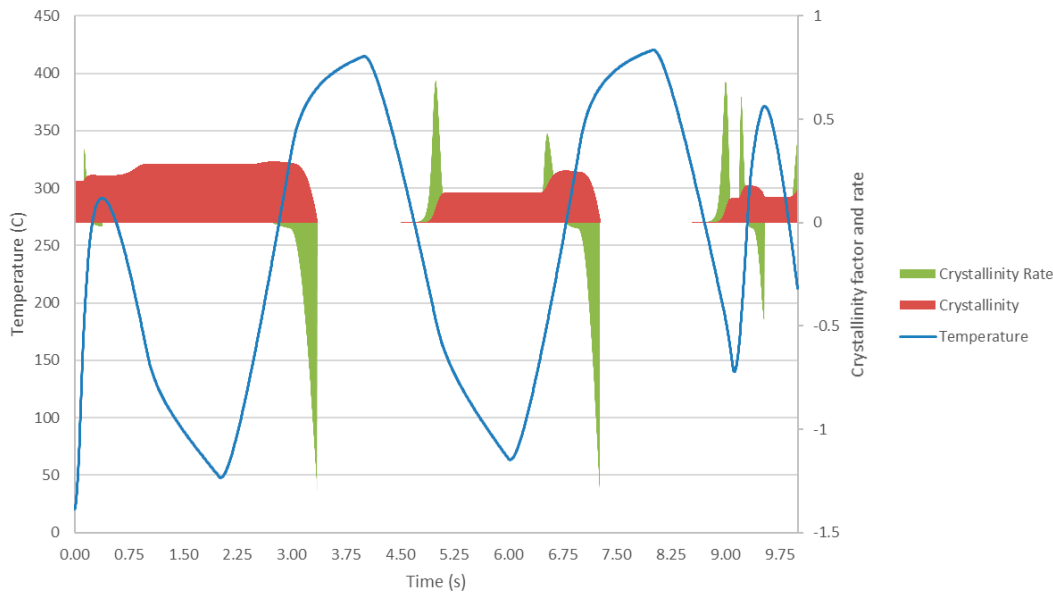


Figure 7: Model results based on PEEK reference material. Temperature (blue line) variation cycles above melt and cooldown (between 50 degrees Celsius and 400 degrees Celsius) and resulting effect on the crystallinity rate (green area) and crystallinity (red area). Crystallinity variation in the range of 0 to 30 % (factor of 0.3) can be observed

From these results it can be concluded that the subroutine works as expected. It includes the crystallinity formulations and the melting kinetics of the thermoplastic material and overall thermal response such as limited exothermal reactions. With these results the fibre placement manufacturing and welding temperature variations are investigated to determine the resulting crystallinity which is relevant for the final manufacturing. In Figure 8 literature results of temperature measurements during the fibre placement manufacturing are shown [7].

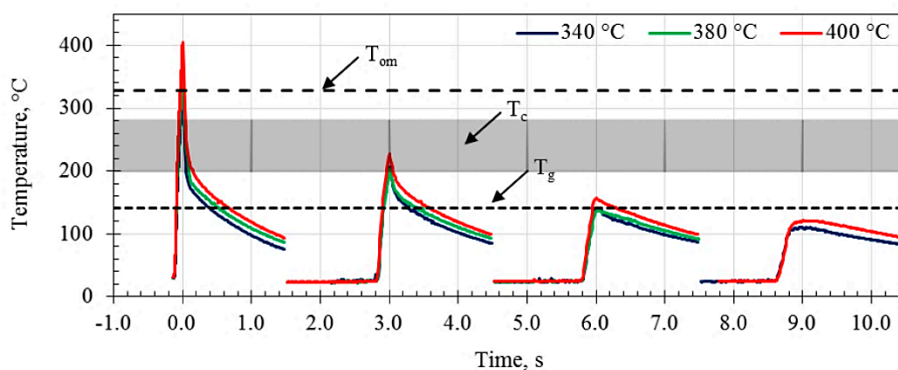


Figure 8: Fibre placement manufacturing and temperature measurements at different layers. The crystallinity range is indicated with T_c in grey [7]

According to this study during the fibre placement manufacturing the cooldown rate is very high, up to 1000° Celsius per second. When going to Figure 6 on the right this shows that after fibre placement manufacturing the crystallinity is expected to be very low. This low crystallinity and high amorphous ratio will have a definitive consequence on the overall thermoplastic material behaviour in terms of strength and stiffness. It has to be noted that for manufacturing a consolidation step will follow after fibre placement.

For induction welding the crystallinity is more critical since this is after the consolidation step in the manufacturing. In experimental results from literature shown in Figure 9 one indicative result on induction welding is shown [9].

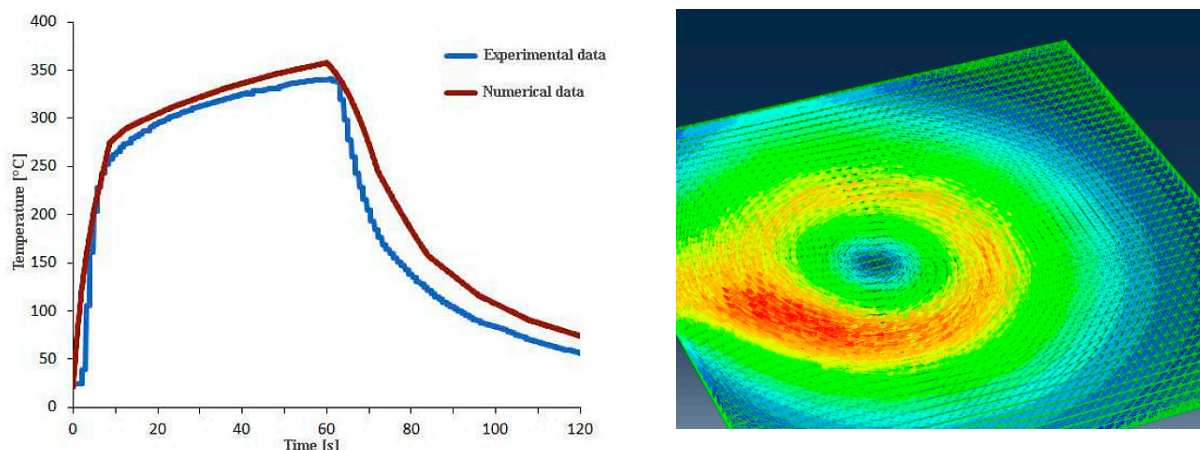


Figure 9: Experimental results from induction welding during heating and cooling. From the experimental results in the crystallinity region a cooldown rate of 20 to 40 °C/s is obtained [9]. On the right the induction welding simulation electromagnetic field output currently under development

With this induction welding cooldown rate in the crystallinity temperature region extracted from the results of 20 – 40 °C/s the resulting crystallinity as shown in Figure 6 on the right is about 5%. This is low compared to the maximum value of 25 – 30 %. This needs to be further aligned with actual measurements during the process. Integration of the material model into the welding simulation is a current effort. Following the temperature and crystallinity investigation the focus is shifted to the mechanical part, the residual stress and distortion.

The focus for the distortion prediction is on the fuselage skin near the passenger (PAX) door since in this region the laminate thickness changes considerably and multiple ramp zones are present. A FE model was created including multiple laminate thickness variations using finite element software Abaqus for the skin level, see Figure 10.

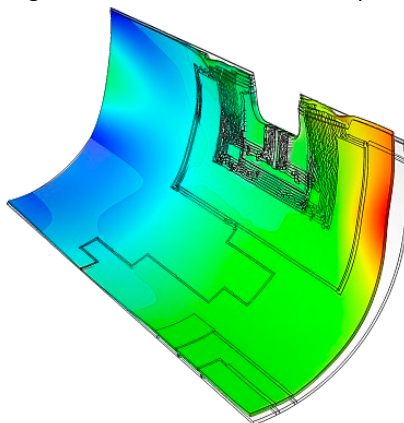


Figure 10: Deformed finite element model of the fuselage skin near the PAX door to be manufactured using fibre placement technology at NLR

A simplified distortion method using thermal expansion coefficients for the fuselage skin has been developed to gain insight and predict trends. The ramp zones or ply drops in the skin are of main interest since here local asymmetry in the laminate is present which can cause distortion of the laminate during cooldown. Estimated values for the coefficient of thermal expansion are used. The fuselage skin finite element model was made using Abaqus composite modeler of the passenger door area including the laminate in detail. After the first results the skin model was further refined in the ramp zone areas. In the updated model the mesh alignment in these ramp zones was improved to enable better predictions of the distortions, see Figure 11.

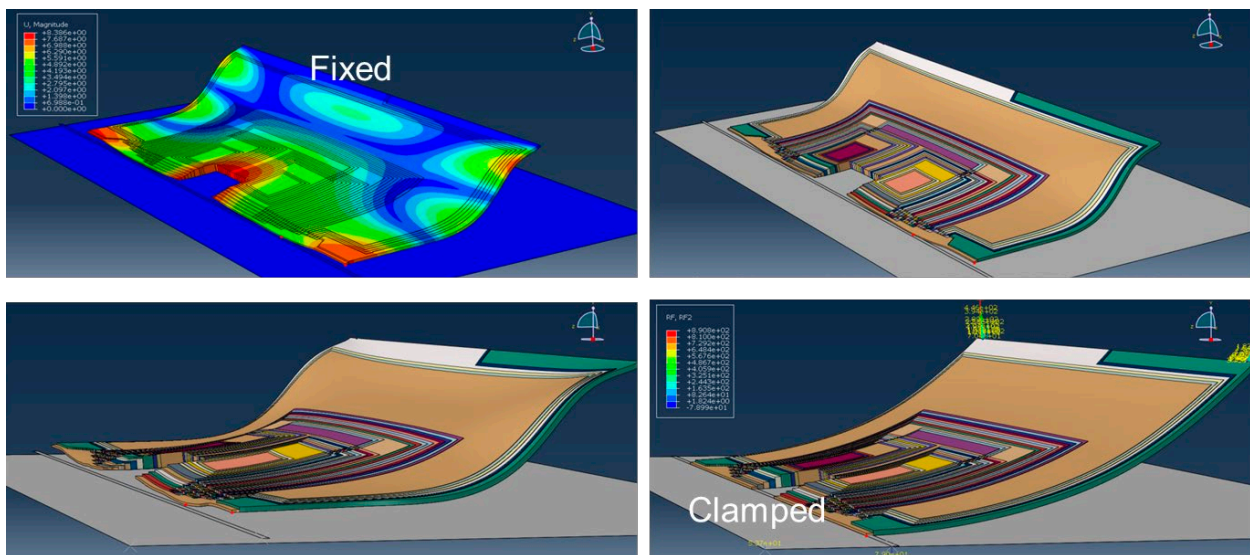


Figure 11: Fuselage skin section finite element model near the passenger door area. An overview is shown of the skin distortion when fixed on the right long edge and followed by clamping. This clamping is used to straighten the distorted edge of the skin

Overall the distortion along the longitudinal edge is around 8 mm out of plane (over the section length of 4700 mm x 1700 mm), Figure 11. The refined and aligned mesh (4 elements per ramp zone) from the CATIA model was used as the basis for Abaqus composite modeller. It appears the shell is globally double curved which is probably caused by the asymmetric layup in the ramp zones. The local effects of the asymmetric ramp zones however are minimal. Still there are uncertainties which are the material properties and the difference in temperature used for the cooling down of the thermoplastic composite.

The distortion calculation is followed by a step clamping step to flatten the skin to enable further assembly of the skin parts without issues. This clamping step works well with Abaqus implicit mainly because the distortion trend prediction seems low. Because of this low absolute distortion and the flexibility of the skin the correcting force for flattening the skin needed is low at 80 N. For future work calibration and validation will be performed and might also include mould interaction and shrinkage in the simulations.

5 Conclusions and recommendations

In this contribution the carbon fibre thermoplastic processing material model that has been developed in the STUNNING project is presented. The material is calibrated using DSC data for high performance thermoplastic material which is used for prediction of temperatures and crystallinity during the processing steps, e.g. fibre placement, welding, consolidation. It shows that due to the processing conditions the final crystallinity does vary considerably. Due to lack of mechanical process material data a simplified approach is used on a higher level for (trend) prediction of the residual stress and distortion in parts of the fuselage skin after fibre placement. This shows that distortion is present however because of the flexibility of the part it can be removed with a small force applied.

It can be concluded that the virtual processing models give valuable insight in the manufacturing process and allows for improvement of the actual manufacturing.

Acknowledgements

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Disclaimer

The results, opinions, conclusions, etc. presented in this work are those of the author(s) only and do not necessarily represent the position of the JU; the JU is not responsible for any use made of the information contained herein.

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