Kurzfassung der Dissertation

Bei der Aushärtung von Hochleistungsverbundwerkstoffen tritt ein prozessinduzierter Verzug auf, der für die nachfolgenden Montageschritte ein Risiko darstellt. Eine Vorhersage dieser Verzerrungen ermöglicht die Bewertung dieser Risiken und Planung adäquater Gegenmaßnahmen noch vor der Investition in Fertigungsanlagen und hat daher das Potenzial, die durch Nacharbeiten verursachten Kosten zu reduzieren sowie zur Vereinfachung des Entwicklungsprozesses beizutragen.
Während in der Literatur viele Methoden zur Vorhersage prozessinduzierter Verzerrungen zu finden sind, haben sich diese Methoden in der Industrie noch nicht etablieren können. Daher liegt ein Schwerpunkt dieser Arbeit darin, Methoden zu finden, die gut in die industriellen Entwicklungsprozesse eingebettet werden können.
In dieser Arbeit liegt der Fokus auf der Vorhersage prozessinduzierter Verzerrungen für den Prepreg-Autoklav-Prozess in Kombination mit den Prepreg-Materialien der neuesten Generation, die Interleaf-Schichten enthalten. Ein Einfluss dieser Interleaf-Schichten auf den prozessinduzierten Verzug wurde experimentell nachgewiesen, es wurde in der Literatur jedoch noch kein Ansatz präsentiert, diesen Einfluss zu quantifizieren.
Basierend auf einer Literaturstudie wurde festgestellt, dass zwei Ansätze erforderlich sind, um den größten Nutzen für den Entwicklungsprozess zu erzielen: den schnellen phänomenologischen Ansatz und den detaillierteren, aber langsameren physikalischen Ansatz.
Als Grundlage für die Validierung beider Methoden wurden experimentelle Untersuchungen mit Coupon-Proben durchgeführt.
Aufwölbung und den Spring-In berechnet die phänomenologische Simulation auf der Grundlage von Materialparametern, die anhand von experimentellen Ergebnissen kalibriert werden. Diese Kalibriercoupons können mit Standardequipment aus der Fertigung hergestellt und ausgewertet werden. Es wird eine einfache Kalibrierroutine vorgestellt, die ohne spezielle Software von jedem FEM-Ingenieur ausgeführt werden kann. Die Methode eignet sich daher als Standardmethode zur Bewertung von Verzerrungen für die meisten Anwendungen. Es wird gezeigt, dass der Ansatz für Materialien mit Interleaf-Schichten gut funktioniert.
Der zweite Ansatz ist ein physikalischer Ansatz, bei dem die physikalischen Vorgänge im Aushärte-Prozess simuliert werden und der daher weitergehende Untersuchungen erlaubt. Vorhandene Methoden zur Materialcharakterisierung werden untersucht und ein für die Untersuchung geeignetes Versuchsprogramm für das untersuchte Material zusammengestellt und erfolgreich durchgeführt. Geeignete Materialmodelle für die Aushärtungskinetik, den Gelpunkt und die chemische Schrumpfung können der Literatur entnommen werden. Für die Materialsteifigkeit sowie für die Wärmeausdehnung werden neue Modelle vorgestellt, die die experimentellen Ergebnisse abbilden können. Zusätzlich wurden neue Meso-Skalen-Mischungsregeln entwickelt, die nach Kenntnis des Autors die ersten sind, die den in Versuchen gefundenen Einfluss der Interleaf-Schichten auf den Verzug erklären und modellieren können. Die Anwendung beider Methoden anhand eines beispielhaften Bauteils zeigt, dass beide Methoden in der Lage sind, den Verzug mit einer adäquaten Genauigkeit vorherzusagen.

Abstract

During the cure of high performance composite materials process induced distortions occur, which causes risks concerning the subsequent assembly steps. A prediction of these distortions allows the assessment and mitigation of these risks prior to investments in manufacturing equipment as jigs and tools and has therefore a potential to reduce costs caused by rework as well as the potential to simplify the development process.

While many methods to predict process induced distortions can be found in the literature, those are not applied as a standard procedure in the industry. Therefore a focus of this thesis is, to find methods which can be embedded well within the industrial processes.

In this thesis the focus is on the prediction of process induced distortions for the prepreg-autoclave process in combination with the newest generation prepregs with interleaf layers. An influence of these interleaf layers on the process induced distortions has been found experimentally, but no approach to quantify this influence has been found in the literature.

Based on a literature study it is concluded that two approaches are needed to provide the most value in the development process: the fast phenomenologic approach and the more detailed but slower physical based approach.

As a basis for the validation of both methods, experimental investigations using coupon-sized parts have been performed. The phenomenological simulation calculates the warpage and spring-in phenomenon based on material parameters calibrated to experimental results. These calibration coupons can be produced and evaluated with standard manufacturing equipment. A simple calibration routine is presented, which can be executed without special software beyond commercial FEM-programs by any FEM-engineer. The method is therefore appropriate as a standard method to evaluate distortions for most applications. It is shown that the approach works well for materials with interleaf-layers without further considerations.

The second approach is a physical based approach, where the actual physical process is simulated. The approach is therefore capable of further process investigations than the phenomenologic approach. Existing methods for the material characterization are investigated and an experimental program appropriate for the investigation is comprised and successfully employed for the investigated material. Appropriate material models for the cure kinetics, gel point and the chemical shrinkage are found in the literature. For the material stiffness as well as for the thermal expansion new models are developed to fit the experimental results. Additionally new mixture rules have been developed, which are to the authors knowledge, the first to explain and model the effect of the interleaf-layers found in the experimental campaign.

The application of both methods to an exemplary part demonstrates that both methods are capable of providing results in line with the measurements.

1 Introduction

The world bank estimates a number of 2.208 billion air passengers for the year 2008 and a number of 4.233 billion passengers for the year 2018. The growth of the aerospace industry is such that in the last ten years, the number of passengers has nearly doubled [1].

To allow this growth to continue in a sustainable way, the resource consumption of aircrafts has to be reduced. Lightweight design is crucial to ensure a high efficiency of the aircraft and therefore a low resource consumption. Carbon-fiber reinforced plastics (CFRP) have proven to be a beneficial material for lightweight design and are employed to an extend of more than 50% of the mass in current aircraft generations as the Airbus A350 and the Boeing 787. For the latter it is estimated that the fuel consumption is 20 % below that of a comparable aluminum aircraft. Most of the structural parts for these aircrafts are produced in the prepreg-autoclave process [2].

These production processes are associated with specific challenges. One of those challenges is the formation of process induced distortions, which are deviations between the planned and produced part geometry. They are caused primarily by chemical shrinkage due to the curing reaction of the polymer matrix and the thermal shrinkage during the cool-down from cure temperature to room temperature.

The current approach to mitigate process induced distortions is to use empirical correction measures and subsequent iterative experimental optimization to compensate the tooling shape. This process is time-consuming and resource intensive.

A simulation predicting the process induced distortion offers an improved understanding of the mechanisms causing it and allows a knowledge-based process optimization which is faster and less resource intensive than the empirical approach. Therefore, methods for the prediction of these process induced distortions using analytic or numerical approaches have been suggested in the literature.

The goal of this thesis is to investigate, extend and improve simulation methods for the prediction of process induced distortion for the latest versions of the prepreg-autoclave process. Major parts of this thesis have been created in a three-year-sponsorship by the Airbus Operations GmbH and are therefore performed with a special focus on the industrial application of the simulation methods within the aerospace industry.

2 State of the art

2.1 The Formation of Process Induced Deformations

High quality composite parts are widely used as structural components in the aerospace industry due to their advanced mechanical properties. The most commonly used process for the production of these high quality composite parts is the prepreg-autoclave process, which is based on the use of carbon fiber material pre-impregnated with a resin (prepreg).

For the part production the prepreg is manually or automatically stacked to form a laminate with the designed properties. Applied to a mold, the part is cured within the autoclave. As presented in Figure 2.1, a vacuum p_{Vac} is applied at the composite in order to remove volatiles from the resin during the curing process. Outside of the pressure tight vacuum foil covering the part the autoclave pressure p_{Akl}, which is usually in the range of $5\,\mathrm{bar}$ to $10\,\mathrm{bar}$, is applied in order to consolidate the laminate and thereby decrease porosity to an allowed extend.

As the resin cures, single monomers react and form long polymer-chains, replacing weak van-der-Waals connections between the molecules by strong covalent bonds. The progression of the chemical curing reaction is indicated by the degree of cure α. This process is shown in principle in Figure 2.2. The crosslinking of an epoxy resin at room temperature occurs at a low reaction rate (a) therefore the temperature of the resin is increased, thus increasing the specific volume of the material (b). The monomers react with each other and start to form short chain-molecules. With the reaction the specific volume decreases (c) leading to an increased density of the fully cured material (d).

The idealized volume change caused by thermal expansion and chemical shrinkage is shown over the process temperature in Figure 2.3. Between the points a and b the uncured resin is heated to the curing temperature, causing thermal expansion. The volume of the resin increases. When the curing temperature is reached at point b, the chemical reaction occurs, causing chemical shrinkage. The volume of the part decreases at the constant cure temperature between point b and c. Once the curing is completed, the temperature is decreased, causing thermal contraction. As the state of the resin has changed from a liquid to a solid, the thermal expansion coefficient (CTE) has changed, leading to a different slope at the cooldown between point c and d. It shall be noted, that in reality, the curing reaction is

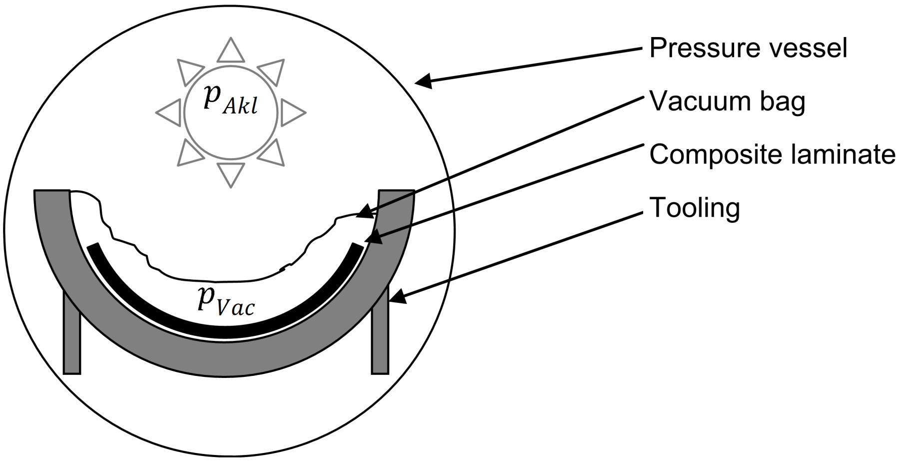

Figure 2.1: Principal setup for the manufacturing of composite parts in the autoclave

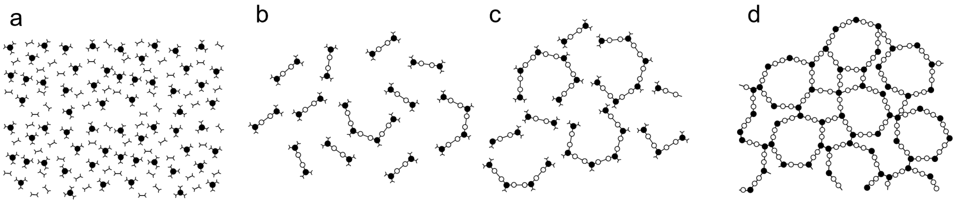

Figure 2.2: Curing of thermoset resin (a) monomer stage, (b) linear growth and branching, (c) formation of gelled but incompletely cross-linked network and (d) fully cured thermoset based on [3]

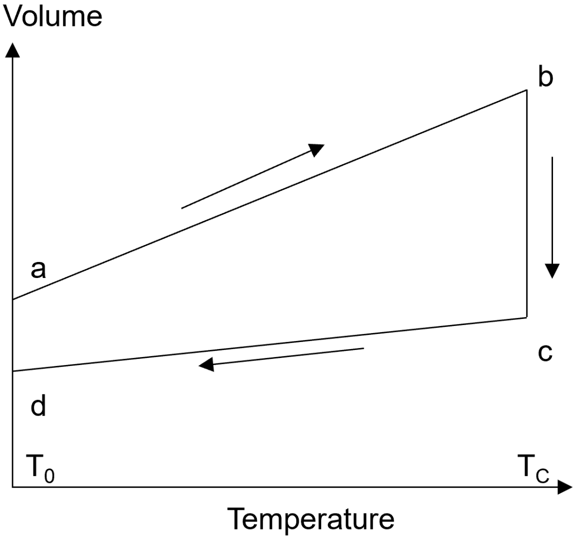

Figure 2.3: Volume change of thermoset resin (a) monomer stage, (b) linear growth and branching, (c) formation of gelled but incompletely cross-linked network and (d) fully cured thermoset based on [3]

already occurring at lower temperatures, therefore a superposition of thermal expansion and chemical shrinkage is observed. Furthermore the linear relation indicated in the figure is not present in reality as the material parameters are not constant but temperature dependent.

With the progression of the curing reaction, not only the volume and CTE is changing, but also the viscosity of the epoxy resin increases, as shown in Figure 2.4. The resin viscosity increases up to a point, where the polymer-chains have reached a sufficient length to endure prolonged loads. This point is called the gel point or point of gelation indicated by the degree of cure α_{gel}. Below this degree of cure the material is in a liquid state. Stresses which arise in this state due to chemical shrinkage and thermal expansion relax completely in the process timescale and have therefore no major influence on the process induced distortions [4]. At the gel point the material behavior changes from a viscous to visco-elastic material behaviour as the gel point coincides with the first appearance of an equilibrium modulus or relaxation modulus. Therefore stresses arising after gelation do not fully relax and have a lasting influence on the process induced distortions. Gelation does not affect the rate of cure and the reaction continues beyond the gel point to complete the network formation. The phase were the material behaves visco-elastic is called rubbery phase.

As the glass transition temperature of the polymer T_g increases due to the chemical crosslinking T_g exceeds the cure temperature T at the vitrification point. The resin transitions into the glassy phase, the rate of crosslinking slows down and the reaction mechanism changes from a chemical controlled reaction into a slower diffusion controlled reaction. Full diffusion control is reached roughly if the glass transition temperature is $20\,^{\circ}\mathrm{C}$ above the cure temperature. After vitrification the material behaves elastic. Residual stresses caused by chemical shrinkage and thermal expansion in the glassy state do not relax during the timescale of the process