Kurzfassung der Dissertation

Um eine hohe Bauteilqualität bei geringen Herstellungskosten zu erreichen, wird zunehmend die Simulation des Herstellungsprozesses verwendet, um die Wärmeübertragung und die Härtungsleistung während des Autoklavenprozesses vorherzusagen. Der große Vorteil dieses Ansatzes ist eine deutliche Reduzierung des experimentellen Aufwands im Vergleich zu herkömmlichen empirischen Verfahren. Eine effiziente und kostengünstige numerische Methodik stellt jedoch nach wie vor eine Herausforderung dar, die eine breite Anwendung in der industriellen Praxis insbesondere für eine komplizierte Fertigungsumgebung verhindert. Daher ist es dringend erforderlich, aktuelle numerische Verfahren durch eine systematische Untersuchung zu ergänzen.

In dieser Arbeit wurde ein dreidimensionales numerische Strömungsmechanik-Finite Elemente Methoden gekoppeltes Modell zur Modellierung der konjugierten Wärmeübertragung vorgeschlagen. Der methodische Rahmen wird vorgestellt, um den Herstellungsprozess, der multiphysikalische Kopplungseigenschaften aufweist, durch neuartige numerische Techniken effizient und korrekt zu analysieren und zu optimieren. Es wird ein Konzept des „schnellen virtuellen Autoklaven" verwendet, bei dem diese numerischen Techniken eine schnelle thermische Analyse während der Verarbeitung mit angemessener Vorhersagegenauigkeit ermöglichen.

Es wird eine systematische und parametrische Studie zur effizienten Prozessmodellierung durchgeführt und wesentliche Einflussfaktoren auf das Autoklavenmodell untersucht. Zur Beschleunigung des Simulationsprozesses wird ein effizientes Kopplungsverfahren entwickelt. In jedem werden numerische Ergebnisse mit experimentellen Ergebnissen verglichen und die sensible Analyse der zugehörigen Modellparameter durchgeführt. Eine systematische experimentelle Validierung der numerischen Methodik für eine komplizierte Fertigungsumgebung wird ebenfalls bereitgestellt. Es wird eine auf maschinellem Lernen basierende thermische Optimierung vorgeschlagen, die den Simulationsprozess weiter optimiert.

Diese Arbeit präsentiert eine detaillierte und effiziente numerische Methodik zur Vorhersage der Wärmeübertragung bei der Autoklavenverarbeitung und bietet Richtlinien zur Optimierung des Herstellungsprozesses auf eine sehr nützliche und wirtschaftliche Weise.

Abstract

To achieve a high part quality at low manufacturing costs, manufacturing process simulation has been increasingly used to predict heat transfer and cure performance during the autoclave process. The major advantage of this approach is a significant reduction of experimental effort compared to traditional empirical techniques. However, an efficient and cost-effective numerical methodology is still a challenge, which prevents a widespread application in industrial practice, especially in a complicated manufacturing environment. Therefore, there is a critical need to supplement current numerical techniques with a systematic study.

In this work, a three-dimensional computer fluid dynamics-finite element method coupled model for the modeling of conjugate heat transfer has been proposed. The methodology framework is presented to efficiently and correctly analyze and optimize the manufacturing process that is multi-physics coupling characteristics through novel numerical techniques. A 'rapid virtual autoclave' concept is employed in which these numerical techniques allow a fast thermal analysis during processing with reasonable prediction accuracy.

A systematic and parametric study on efficient process modeling is performed, and essential influencing factors affecting the autoclave model are investigated. An efficient coupling procedure is developed to accelerate the simulation process. In each, numerical results are compared to experimental results and the sensitive analysis of related model parameters is performed. Systematic experimental validation of the numerical methodology for a complicated manufacturing environment is also provided. A machine learning-based thermal optimization is proposed, which further optimizes the simulation process.

This work presents a detailed and efficient numerical methodology to predict heat transfer of autoclave processing and provides guidelines for optimizing the manufacturing process in a highly useful and economical fashion.

1 Introduction

During the past decades, carbon fiber reinforced plastics (CFRPs) have been extensively used in aerospace applications owing to their advantages of low density combined with high mechanical properties. In comparison to most metallic materials, CFRPs show high specific stiffness and strength, as well as a lack of self-corrosion [1–3]. In addition, the possibilities of manufacturing highly integral components are fully exploited in modern aircraft, leading to a considerable weight reduction. For example, the content of the CFRP structure exceeds 54% in the Airbus A350XWB [4, 5]. However, these advantages are usually overshadowed by their high manufacturing costs. To achieve high quality and low costs, an optimal manufacturing process implemented in the design phase is necessary to efficiently produce CFRP components.

The required manufacturing devices or methods are often complex, which are difficult to optimize owing to a large number of desired requirements [6]. Exploiting the inherent suitability of composites is one of the most straightforward paths in the manufacturing of large and complex structures, which requires no extensive conditions, e.g., machining and fastening operations [7]. One difficulty associated with this path is developing robust manufacturing processes that can consistently produce high-quality structures while meeting strict tolerance limits. To meet these objectives, the experience-based traditionally entailed trial-and-error processes, which are time- and cost-intensive, are generally conducted in the design phase. Furthermore, this achieved experience from previous manufacturing optimization has often difficulty adapting to new structure geometries, new manufacturing technologies, and new materials. A complete understanding of physical effects during manufacturing processes is of major importance to overcome these issues, thereby reducing the risk such as defects and rejects, as well as minimizing costs, especially for large and highly integrated CFRP components. Based on this extended process understanding, a numerical methodology, which improves the experimentally acquired knowledge, can be implemented for systematically parametric studies and sensitivity analyses. Modern processing simulation techniques are capable of investigating the physical effects, indicating great potential for the investigation of manufacturing process mechanisms [8–11].

1.1 Overview of autoclave processing

In general, large structural CFRP components are manufactured through autoclave processing, which provides parts with a low porosity and low fiber ondulations [1, 12], for high-performance applications. Using this technique, thin layers of high modulus fiber impregnated with prepreg are cut and stacked to form a component of the desired shape. The structure of the cure assembly, which is covered with various auxiliary materials, is sealed inside a vacuum bag, as illustrated in Figure 1.1. The entire cure assembly is then placed inside an autoclave and subjected to a predetermined cure cycle, which defines the temperature and pressure over time, as shown in Figure 1.2. The objective of this cure cycle is to cure the resin and promote resin flow, thereby obtaining an optimum resin content and a void-free component [13, 14]. A particular cure depends on the chemical reaction characteristics and physical properties of various resin systems [15]. Meanwhile, the dimensions of the cured part should be within preset tolerance limits [7].

The main challenge of autoclave processing is to attain a robust and optimal manufacturing process combining the cure cycle, tool design, and a bagging procedure definition in

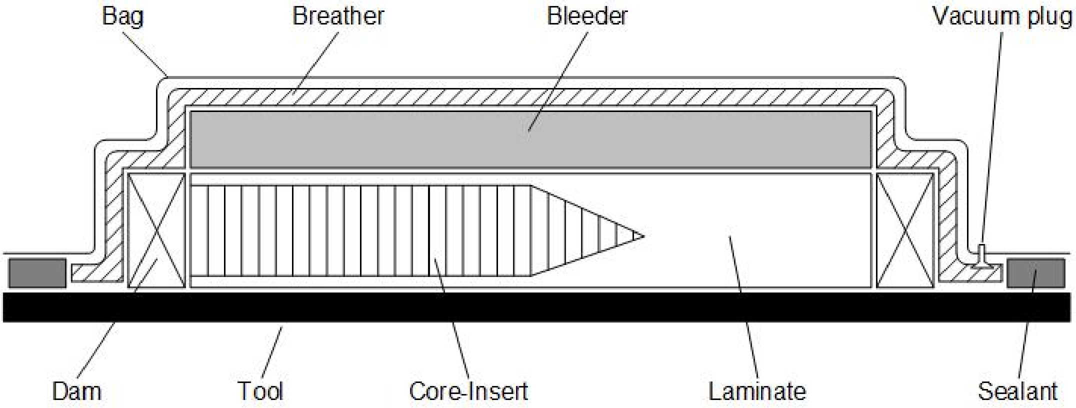

Figure 1.1: Component and tooling prepared for autoclave processing

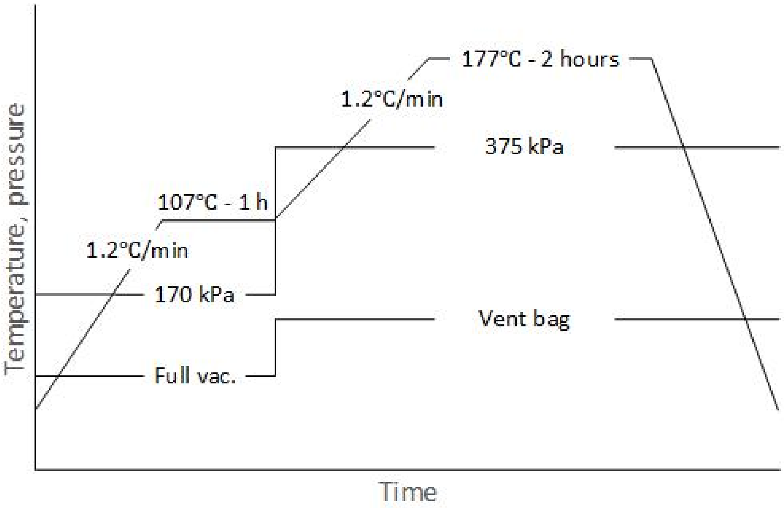

Figure 1.2: Typical cure cycle of autoclave processing

the shortest time and the most economical fashion [14]. Therefore, forecast potential problems, which might arise owing to random changes in process variables, are necessary to help minimize process variation. Efforts have been made to deal with these issues. There are shortcomings in early developed methods. For example, traditionally entailed trial-and-error modifications are costly and time-consuming, especially when applied to large complex structures [16–18]. In addition, the use of intelligent process control has disadvantages such as disallowed prediction of processing outcomes, unavailable insight for process design, material dependent, and inflexible modification [7].

However, these shortcomings can be addressed through modern simulation techniques. To meet these objectives, numerical models are developed for the physical effects involved in autoclave processing. Using these models, the autoclave processing can be simulated to examine the rationality of the process, tooling and part designs, and cure quality of the part. This can reduce the cycle time, and costs from trials and development significantly [14].

A real autoclave manufacturing system indicates typical multi-physics coupling characteristics. During the curing process, forced convection in the flow region with simultaneous heat conduction through the composite parts is referred to as a conjugate heat transfer problem. As the temperature increases, the resin undergoes a cross-linking chemical reaction, and the heat released by the reaction can affect the temperature field [19, 20]. In the course of the curing reaction, there exist changes in the modulus of the resin and the mechanical properties of the parts [21, 22]. Therefore, the curing process of composite materials is a multi-physical coupling process, involving the mutual coupling of multiple fields such as airflow field, temperature field, cure kinetics, material properties, stress, and deformation. Generally, this complex coupled problem is divided into a series of simpler problems. Coupling models are solved each in sequence as the solution marches in time [23]. The use of submodels is necessary to be integrated into the coupling system [24]. For example, computational fluid dynamics (CFD) provides a significant contribution to studies on airflow patterns and heat transfer, which are key points in an optimization applied to achieve a homogeneous temperature distribution inside composite parts. In addition, the cure model for cure rate definitions has a significant influence on heat generation. Furthermore, the resin flow model is used to predict resin flow and fiber bed compaction, which directly affects the development of residual stress and deformation. Moreover, boundary conditions between the models must be given for accuracy and robust computations. In this coupled system, the results obtained from one model can be used by another. According to the development of the various phenomena, the autoclave processing simulation mainly consists of:

- CFD simulation: simulates the airflow field and heat transfer in the autoclave, and other parameters associated with structure boundary conditions such as local heat transfer coefficient (HTC).
- Thermochemical simulation: predicts temperature distribution within the structure and tooling and the degree of cure in composite structural components.
- Resin flow simulation: predicts resin flow and fiber bed compaction in composite parts.
- Thermomechanical simulation: simulates the development of residual strain and deformation in the structure and tooling.

During the past decades, there have been a number of studies and analyses conducted on the composites process modeling which describe the phenomena listed above. Despite the significant advances in the research of process modeling, most currently available process models remain without a systematical, effective and economical approach in autoclave process development, especially for complex composite structures and loading conditions, which prevents a widespread application in the industrial practice.

1.2 Motivation and research objectives

During the autoclave curing process, a uniform temperature distribution is important to achieve homogeneous curing and therefore reduce the process-induced distortions [25–27]. The temperature distribution within the CFRP component is largely influenced by forced convection, which is generally characterized by a heat transfer coefficient (HTC) [28]. To ensure homogeneous curing and improve the curing performance, thermal optimization within the autoclaves is required.

Owing to the ever-increasing power of computer hardware the prediction of heat transfer through a numerical simulation is of major importance for the thermal optimization of the autoclave curing process compared to the traditionally entailed trial-and-error modification [17], which is expensive and time-consuming. To study the thermal behavior of composites during the curing process, different prediction models have been developed. In early studies, one- or two-dimensional models were proposed for the thermal and curing simulation. Loos and Springer [29] developed a one-dimensional model to simulate the curing