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A fast method for the generation of boundary conditions for thermal autoclave simulation

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ABSTRACT

Manufacturing process simulation enables the evaluation and improvement of autoclave mold concepts early in the design phase. To achieve a high part quality at low cycle times, the thermal behavior of the autoclave mold can be investigated by means of simulations. Most challenging for such a simulation is the generation of necessary boundary conditions. Heat-up and temperature distribution in an autoclave mold are governed by flow phenomena, tooling material and shape, position within the autoclave, and the chosen autoclave cycle. This paper identifies and summarizes the most important factors influencing mold heat-up and how they can be introduced into a thermal simulation. Thermal measurements are used to quantify the impact of the various parameters. Finally, the gained knowledge is applied to develop a semi-empirical approach for boundary condition estimation that enables a simple and fast thermal simulation of the autoclave curing process with reasonably high accuracy for tooling optimization.

1. Introduction

Today's aerospace composite parts require perfect quality with reasonable manufacturing times and costs. A process step that influences quality as well as manufacturing times is the autoclave curing process. Very often integral and complex parts require complex and heavy molds. Due to the vast set of requirements concerning handling, weight, demolding, thermal expansion, and geometrical tolerances the thermal properties of the mold are often neglected or at least treated with lower priority. The result is an increased manufacturing time due to slow heating rates and reduced part quality on account of high temperature gradients within the part. An optimization from a thermal point of view becomes important, when the necessary quality is not achieved, the manufacturing rate is increased, or the autoclave capacity becomes a bottle neck. In aviation industry some molds are processed alone and might have autoclave cycle times of up to 14 h. A reduction by only 15% means a saving of two hours per cycle, which can avoid autoclave capacity shortages or the necessity to duplicate tooling to reach the desired production rate. Furthermore, a thermal optimization might improve the homogeneity of the temperature field, which in turn has a positive influence on process-induced deformations [1]. To incorporate such a thermal optimization into the tooling design, fast and reliable methods for thermal simulation must be provided. Standard finite element (FE) codes such as *ABAQUS*™ have great potential for such simulations, but modeling the heat transfer from the autoclave air to the mold "efficiently" is still challenging [2–4].

Forced convection is the main source of heat transfer into the autoclave mold [2–4]. Its effectiveness is summarized by the heat transfer coefficient (HTC) between circulating air and the tooling surface and depends on five major parameters [2,3,5–9]: (1) type of flow, (2) flowing medium, (3) flow velocity, (4) static pressure, and (5) temperature. Pressure and temperature are dictated by the necessary autoclave cycle to achieve correct compaction and curing. With respect to shape and working principle, the flow within the autoclave is mainly turbulent [2,3,5,6]. Additionally, varying loading conditions and aerodynamically unfavorable tooling shapes contribute to the turbulence of the flow [2,3]. The turbulence has a significant impact on the HTC, making it extremely difficult to determine the correct boundary conditions for a thermal FE simulation of the manufacturing process. Johnston et al. [2,10], Slesinger et al. [3], and Telikicherla et al. [5] confirmed this behavior through measurements and computational fluid dynamics (CFD). A variation in flow velocity from 1.5 m/s to 18 m/s and a variation of the HTC from 20 W/m^2 K to 180 W/m^2 K within a single autoclave are not uncommon [11]. Especially

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around larger molds with excessive support structures, the flow velocity is often significantly reduced, thus impacting not only the heating behavior of those larger molds but also of every mold placed downwind (leeward) in the autoclave [11]. An additional influence that has to be considered is the position within the autoclave [12,13]. Ghariban et al. [13], Johnston [2] and Hudek [12] showed that the HTC in the front and the back of an autoclave might differ by a factor of 1.3–3.0, depending on the Reynolds number of the autoclave flow.

To enable thermal mold optimization by means of manufacturing process simulation (MPS), these factors must be accounted for in the simulation. In particular, the correct prediction of the heat transfer coefficient is of major importance for providing accurate simulation results [2,3,5,10,12]. Hudek [12] showed that a predicted HTC value, which is ±30% too high, will almost cause a doubling of the error in temperature prediction. Most of the older thermal and curing simulation approaches are one or two-dimensional models only. As boundary conditions, they apply the autoclave temperature directly to mold and part surfaces or use a constant HTC throughout the complete autoclave cycle [2,5,3]. Examples of these approaches can be found in Loss and Springer [14], Twardowski et al. [15], Bogetti and Gillespie [16], and Hojjati and Hoa [17]. An improved boundary condition definition introducing the changes in HTC caused by variations in autoclave temperature and pressure was first proposed by Johnston [2]. Johnston [2] and Telikicherla [5] recognized the importance of considering the autoclave flow velocity and shadowing effects of the manufacturing molds but did not provide an adequate way of incorporating them into the simulation. Xie et al. [4,18] as well as Telikicherla et al. [19] drew on CFD simulations instead of using a solid mechanics finite element method (FEM) solver to generate a three-dimensional representation of the temperature field within an autoclave mold. They considered all influencing effects to achieve the highest accuracy possible [4]. However, there are several disadvantages linked to such a CFD approach. Although the current standards in CFD allow an accurate autoclave simulation, a calibration with flow measurements is often necessary to cover all effects like flow obstructions due to vacuum pipes or thermocouple connectors. Moreover, the CFD model requires an extensive model set-up including the autoclave tube, autoclave tables, and all the molds that might be processed together with the one that has to be optimized [11]. Especially in helicopter manufacturing, more than one loading condition can exist for a certain mold as a lot of different molds are combined in a single autoclave cycle. Even the simulation of only the best and worst case loading conditions requires two models and the meshing of molds that are not optimized but just used as dummies for the simulation. Furthermore, the computation time of CFD is rather high and CFD does often not allow an easy transfer of HTC data to a solid mechanics based process simulation. To overcome these difficulties, Hudek [12] conducted a comprehensive study on HTC variations within an autoclave and used this knowledge to develop the thermal boundary condition (TBC) program. This software tool is able to generate the boundary conditions for a solid mechanics based autoclave structural/thermal FE simulation. Hudek [12] and Johnston et al. [10] combined the TBC with additional software modules to develop the virtual autoclave concept. This rather complex software module generates the thermal boundary conditions for mold and composite part from an analytical autoclave flow approximation considering the influences previously named [10,12].

Instead of using lengthy CFD evaluations or additional software tools, a fast method for estimating thermal boundary conditions that combines low numerical and testing effort with reasonable accuracy is presented here. The method uses surface film conditions (standardly available in *ABAQUS*™) enabled by a catalog of adjustment factors to account for intra-part shadowing effects, different longitudinal positions within the autoclave, and changing loading conditions (inter-part shadowing). This approach reduces model set-up and computation times to the level of those applying only a constant HTC throughout the complete simulation. Furthermore, the simulation is limited to the mold that is actually under optimization but still enables the comparison of different autoclave loading conditions. The automation possibilities within *ABAQUS*™ and its reasonable accuracy demonstrate great potential for an industrial application and the integration of a thermal mold optimization into the tooling design process.

2. Measurement procedure, test tooling and autoclave set-up

The measurements of the HTC curves presented in this study are conducted by means of a calorimeter placed at different positions in the autoclave. Various calorimeter designs are available in the literature. Johnston [2], Slesinger et al. [3], Ghariban et al. [20], and Hudek [12] used plate or rod calorimeters made from steel or aluminum. In this study a steel bar calorimeter with six thermocouples (type J, accuracy ±1.5 °C) was used. Various positions within the autoclave and different positions relative to various molds were analyzed (Fig. 1). All designated measurement points were analyzed three times to provide the necessary statistical significance. Additionally, positions 1–3 were analyzed with different pressure cycles to determine the pressure dependence of the HTC. The measurements provided a temperature value every five seconds. The resulting curves were smoothed using a moving average over a one minute interval. The mean flow velocity of the air in the used autoclave (number 1 in Table 3, Section 3.5) is approximately 4 m/s but due to flow inhomogeneity peaks of twice that speed are possible. The flow velocity was estimated by means of calorimeter measurements and Eq. (1). The autoclave cycles are based on the manufacturer recommended cure cycle for Hexcel HexPly *M*18/1™ (see Fig. 3, left).

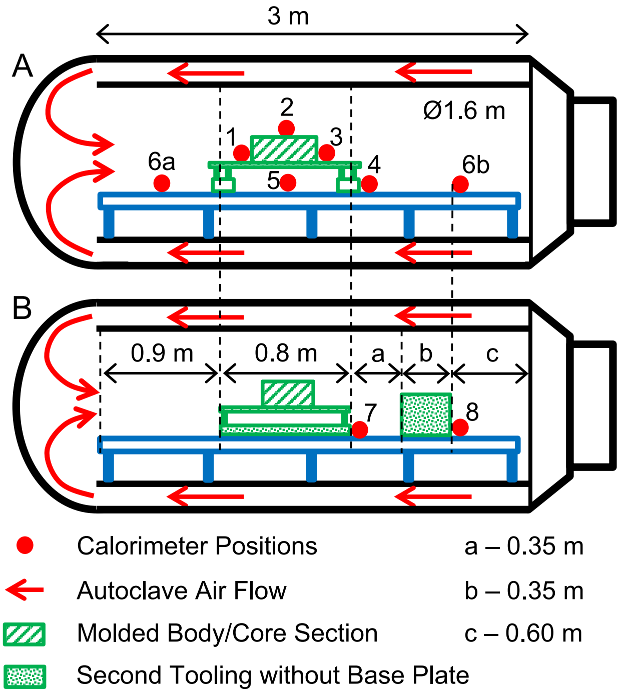

Fig. 1. Different calorimeter positions and loading conditions (A and B) used for the measurements. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)