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Research Paper

Case study of a thermally-assisted manufacturing tool-and-process modeling for design optimization

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ABSTRACT

Thermally assisted manufacturing processes require specific tool and process design that is tailored to undertake thermo-fluid dynamics and part variation. Therefore, most of the tooling designs for such processes start at the solid model but then rely heavily on best practices and experience. To allow for a level of flexibility against variations, an automatic controller is added to monitor and adjust the process. However, controllers are only effective as long as the tool and the process have been optimally designed. The challenge in a thermally assisted process stems from the appropriateness of the design of the solid part that is utilized to apply the thermal energy to materials being processed. This process involves thermo-fluid dynamics influencing the solid part shape and performance, while adapting to variations in material and process parameters. This variation of processed parts increases significantly when these parts are nonmetal, like fiberglass and polymers. Additional challenges come from the competitive nature of the thermal processing business resulting in scarcity of related literature.

The purpose of this case study was to present a methodology for modeling a thermal tool used in a thermally assisted manufacturing process and the thermo-fluid dynamics associated with this tool in operation, for design optimization that will generate the desired product while accommodating normal process and material variation. In this paper, a thermal tool and process are modeled using a hybrid of solid modeling and thermo-fluid dynamics modeling. The resulting model is experimentally calibrated and tested to predict the performance of the tool and process. Results show a very close match between the simulation and experimental data. The model is further implemented to modify the design and results show very close match between the simulation and actual data.

1. Introduction

Thermally assisted manufacturing processes, particularly those of nonmetals, have historically relied on trial and error and experience. Some design of experiments might be involved but with many manual tweaks to follow. The majority of the available literature on thermally assisted manufacturing processes discusses applications to metal cutting, machining, and formation within processes like deposition [1,2]. Literature reports handling thermally assisted manufacturing of nonmetals, like polymers and fiberglass, are not as numerous and are cautiously written when handling particular processes in a competitive market [3]. Nevertheless, certain principles and concepts governing such processes are available in the literature for general guidance [4]. These principles can be traced in literature sharing industrial applications of thermally assisted processes like the vehicle and aerospace industry and the biomedical devices industry. As an example, low-density, glass-mat thermoplastic materials are commonly used in the interior of passenger vessels like vehicles and airplanes. As an example, Hipwell described the manufacturing processes to produce a high-quality low cost soft vehicle interior and the steps needed to speed up the process [5]. In another example, a patent by Rotter described a thermos-formable laminate and some of its manufacturing aspects for use in making orthopedic splints padding for more comfortable application and wear on a patient's limb [6]. Throughout these publications, two items are always provided: the material description and the manufacturing steps. Meanwhile, even with this information, tooling design and process optimization is left out as items dependent on the particulars of the process and product. This leaves the design and construction of related tools and processes to best practices and experiences.

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Conceptually, thermally assisted processes involve tooling that is specifically designed to produce a particular temperature profile applied to the manufactured part. Once an initial solid model is produced for the thermal tool, combined with best practices and experiences, a tool is produced and the process is run for trial and error optimization. A controller is usually added for automatic adjustments of the process to track set points against dynamic changes and variations. However, the controller is usually most effective when the initial tool and process design have been carried out correctly. Sub-optimally designed or performing tools, or processes, will exceed the capacity of a controller to correct errors, or draw more energy rendering the process economically exhaustive. A thorough design and modeling effort is required to bring the tool and process to a level close to the optimal performance which can be supported against normal process variation using a controller. From a process point of view, understanding thermally assisted manufacturing brings up a common challenge stemming from modeling the tool and process for optimal design. This modeling has to take into consideration the combined interaction between the solid tool and the thermo-fluid dynamic effect being experienced by the tool and exerted by the tool on the product. Combined or hybrid modeling approaches including solid modeling, Computational Fluid Dynamics (CFD), thermal modeling, and process modeling, would be more suitable for this situation. Such complex models would help predict performance and optimize the outcome before the manufacturing process is setup and started resulting in superior processes and products in terms of both quality and economy.

In this paper, improvements to an existing thermally-assisted manufacturing process has been developed through trial and error as well as best practices within a company, are discussed. In particular, part material properties, process sequence, and final product quality, contributed to the design requirements of the tool and process. As time progressed, rates of rejection and variation of raw material properties increased, causing significant challenges to the process. Consequently, this turned into a market competitiveness question by the manufacturer triggering a thorough investigation of the process to provide a reliable engineering solution. Therefore, a proper modeling and robust design of the tool and process were sought out to provide enough adaptability to normal variations while establishing the correct engineering base for similar future developments or modifications. This presented a unique case study that can be used as an example of how hybrid modeling of solids undergoing thermal dynamics can be used to predict performance and optimize design before physical investment is carried out.

2. Analysis of original tool and process

The existing heater tool was designed to produce a desired temperature profile and apply heat to the manufactured parts. Heaters and sensors were embedded in the tool to provide both actuation and feedback to a controller (PID type) that would activate the different embedded heaters as needed. A preliminary investigation of the thermal manufacturing process was carried out to identify and monitor influential factors in the process. Since a tool and process already existed, although they were not optimal, data were needed for verification and calibration of both existing and developed models.

A thermal imaging camera was employed to characterize and capture the existing temperature profile of the tool while in operation. The desired profile was supposed to be uniform at all sides of the tool. Fig. 1 presents the heating tool used in the thermally assisted manufacturing process, which measures just over 2′ by 1′. Fig. 2 presents one of the thermal images of the same tool and the actual temperature profile. The figure shows inconsistency with the targeted profile of 650 °F temperature even after settling time has passed and the process was ongoing. In specific, inconsistencies in the temperature profile of the tool were between 100 °F and 200 °F, or 15% to 30% which are quite significant and would cause a remarkable variation in the quality of the final product. Moreover, in spite of the controller being in effect at this settled state, it was largely ineffective, which raises questions regarding the controller itself, but cannot be answered until an optimal design is verified for the heating tool and thermally assisted process. Based on these images and variation in the product quality, as well as an understanding of the process, a decision was made to examine the tool and process further.

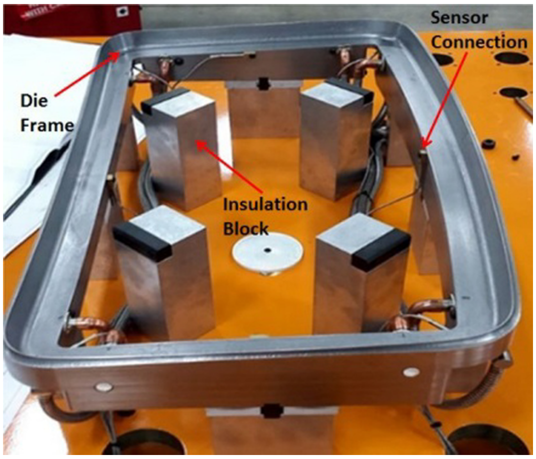

Fig. 1. Heating tool used in the thermally assisted manufacturing process on insulation blocks.

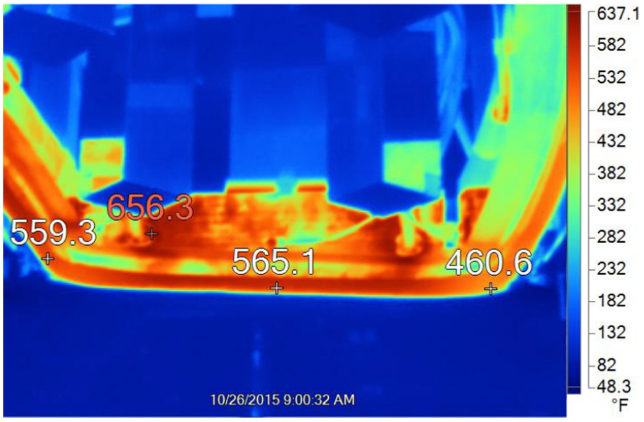

Fig. 2. Thermal image of the tool showing inconsistent temperature profile.

The current heating tool is divided into eight separately controlled heating zones. Fig. 3 shows these zones. Each of the zones has a heater and a Resistance Temperature Detector (RTD) that reads the temperature and sends data to the controller. The heating tool makes contact with the parts at its bottom and inside surfaces. It is to be noted that the heaters are inserted relatively lower at the corner zones compared to the straight zones.

Data was collected from the RTDs during a heating up process from room temperature to 650 °F for the straight zones, and to 680 °F for the corners, at the settling state. Throughout the data collection process, the surrounding room temperature was controlled in order to rule out temperature variance that would affect the readings due to thermal exchange with the surrounding.