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Modeling and characterization of fused deposition modeling tooling for vacuum assisted resin transfer molding process

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Abstract

The material extrusion additive manufacturing process, i.e., fused deposition modeling (FDM), as opposed to traditional subtractive manufacturing, offers a superior way of manufacturing tooling components in terms of great design flexibility, rapid tooling development, material requirement reduction and significant cost savings. However, it is always challenging to design a tool structure with minimized material and labor cost while maintaining satisfactory tooling performance. In the current study, a comprehensive finite element model was developed for ULTEM 9085 FDM tools subjected to applied pressure and elevated temperature for vacuum assisted resin transfer molding (VARTM) process. Both solid-build and sparse-build tools were studied. Material properties of the tools were obtained from solid coupon testing at elevated temperatures. The thermo-mechanical behavior of tools during the VARTM process was investigated using the finite element model. The ULTEM tools were manufactured using Stratasys Fortus 400mc FDM machine. Thermal cycling of the tools was performed at elevated temperatures (180 °F and 250 °F). Dimensional analysis and surface roughness of the tools were evaluated after thermal cycling. This study on the performance of FDM tooling for VARTM composite manufacturing process can be extended to other composite manufacturing processes.

Keywords: Additive manufacturing; VARTM; Finite element analysis; ULTEM

1. Introduction

The fused deposition modeling (FDM) process, as a material extrusion additive manufacturing process, starts by feeding thermoplastic material from a spool of thin plastic filament. Then the thermoplastic is melted in a liquefier head by a resistance heater. Afterwards, the molten thermoplastic is extruded to form a thin layer which is solidified to form a laminate. CNC controls the path of extrusion from the liquefier head position. Layers are deposited on previous laminates and fused together [1,2]. The FDM process possesses great potential to reduce manufacturing costs and lead times while maintaining manufacturing quality and repeatability. Thermoplastic polymers (ABS, Polycarbonate, ULTEM and Polyphenylsulfone) hold great promise for tooling for composite manufacturing and dies for sheet metal forming, in addition to manufacturing 3D end-use parts, especially for high performance thermoplastics like ULTEM 9085. The material has high mechanical strength and high heat deflection temperature. Fire retardancy makes ULTEM 9085 suitable for aerospace and aviation applications. Recently, researchers have been actively investigating ULTEM materials for different end-use part applications, like UAVs [3] and 5.25 ft (1.6 m) aircraft wings [4]. However, not many studies have been performed or published on ULTEM materials for composite manufacturing application at elevated temperatures with the exception of the feasibility study conducted by Stratasys Inc. [5].

Finite element analysis has been widely used in modeling engineering structures and processes, specifically for the FDM application. Costa et al. [6] developed an analytical solution for the transient heat transfer during filament deposition accounting for contacts between filaments. Zhang and Chou [7,8] developed a finite element model to simulate the filament deposition process. The model took the coupled thermal and mechanical phenomena into account and analyzed the stress accumulation and resulting distortion of the parts. Graybill and El-Gizawy [9]

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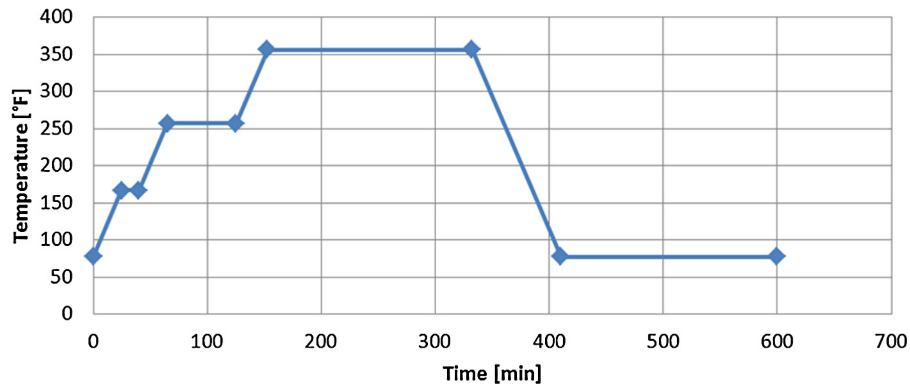

Fig. 1. A typical cure cycle used in VARTM process [12].

implemented a layered method and a bulk properties method to investigate the anisotropy of the ULTEM material. Tensile specimens were built, tested, and compared with simulation results, and good agreement was obtained. In the experimental study, Bagsik et al. [10,11] studied the influence of orientation and toolpath on the mechanical properties of FDM-manufactured ULTEM coupons. Compression and tension tests were performed and ultimate strain and stress were presented. Although some work has been done in both experiments and simulation, most of the previous work is on simulation and modeling of the deposition process and coupon level compressive/tensile testing.

The existing knowledge of using FDM rapid tooling and manufacturing technology is still very limited. The demand of minimizing tool material and labor cost in industry makes sparse-build tooling promising; however, only limited data is available on the performance of sparse-build as well as solid-build tooling components at elevated temperatures. The ULTEM application to elevated temperature composite manufacturing processes is limited to small parts as large ULTEM tools tend to have significant thermal expansion [5]. The VARTM process takes five hours on average at elevated temperatures up to 250 °F or even higher. ULTEM tools must be able to resist the cure cycle of the resin system and accommodate the thermal expansion effect of tools during the curing process. Thermoplastic ULTEM tooling materials have relatively larger coefficient of thermal expansion (CTE) than steel/aluminum tooling materials. Repetitive use of ULTEM tools will develop accumulated dimensional inaccuracy due to substantial heating/cooling. Repetitive thermal expansion and restoration will build up residual stress and ultimately disqualify the tools for manufacturing composite parts with desired dimensions.

To investigate the above issues, in the present study, a fully coupled transient thermo-mechanical finite element model for ULTEM 9085 FDM tools was developed for VARTM process. Material properties of the tools at room temperature (77 °F) and elevated temperatures (180 °F, 250 °F, 300 °F, 325 °F and 350 °F) were obtained through compression tests with cylindrical coupons. A typical cure cycle up to 350 °F was implemented to study the thermal expansion and possible residual stress during the VARTM process. Both solid and sparse-build ULTEM tools with complex geometries were fabricated using Stratasys Fortus 400 mc FDM machine. Thermal cycling experiments were designed and performed to study the dimension accuracy and surface roughness of ULTEM tools after a number of predefined thermal cycles at 180 °F and 250 °F.

2. Thermo-mechanical simulation and modeling

2.1. Modeling ULTEM FDM tool for vacuum assisted resin transfer molding process

VARTM process is an environmentally friendly and low-pressure composite manufacturing process. Although composite parts manufactured using VARTM have a relatively higher void content, the process does not require high pressure as in the autoclave process and thus the associated costs are significantly lower (at least 25% less than autoclaved parts). Complex and large near-net shaped integrated composite parts can be manufactured. However, the process requires elevated temperatures to cure thermoset composite parts. A typical cure cycle up to 350 °F [12] was used to perform transient thermo-mechanical analysis of the ULTEM tool, as shown in Fig. 1. The cure cycle corresponds to Cycom 977-20 toughened epoxy VARTM resin system. In VARTM process, the ULTEM tool is subjected to both atmospheric pressure and elevated temperatures. The geometry of the ULTEM FDM tool used for the current study is shown in Fig. 2. The tool has a flat bottom surface 12 in. × 8 in. (304.8 mm × 203.2 mm) with a curved top surface and different heights along corners and edges. The same surface geometries were used for both solid and sparse-build tools.

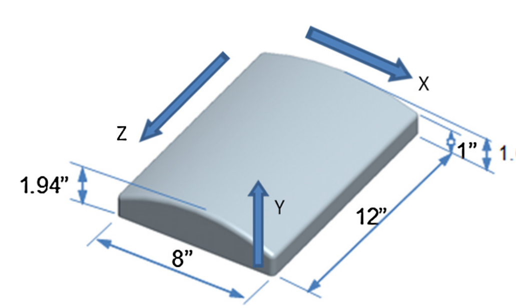

Fig. 2. Geometry of ULTEM FDM tool.

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