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A case study on the capability of rapid tooling thermoplastic laminating moulds for manufacturing of CFRP components in autoclaves

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Abstract

Additive manufacturing (AM) is most used in prototype production and other processes upstream of series production. However, in recent years additive manufacturing has also moved into series production environments substituting for established systems. With AM, it is possible to improve production in terms of material consumption, manufacturing costs, and lightweight design. Accordingly, it is possible to create complexly arched laminating moulds directly from the CAD-model instead of milling them from solid material as is frequently done for the production of carbon fibre reinforced plastic (CFRP) components in autoclaves. This work analyses the potential of CFRP-laminating moulds as rapid tooling moulds generated by fused deposition modeling. A rounded cuboid will be considered with different reinforcement patterns as well as various wall thicknesses. Normal autoclave conditions will be simulated with pressure variation and high temperature stress varying over time. In conclusion, the results prove the capability of rapid tooling thermoplastic laminating moulds for manufacturing CFRP components in autoclaves.

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Keywords: rapid tooling; moulding; autoclave; fused deposition modeling.

1. Introduction

Additive manufacturing [1,2] (AM) is most used in prototype production and other processes upstream of series production. Recently, AM has also moved into series production environments where it is replacing established systems. AM makes it possible to improve conventional production in terms of material consumption, manufacturing costs, and lightweight design. Accordingly, it is possible to create complexly arched laminating moulds directly from CAD-models instead of milling them from solid material as is frequently done for the production of carbon fibre reinforced plastic (CFRP) components in autoclaves. However, mechanical design is still driven by producing components with traditional manufacturing processes [3].

This leads to additive manufactured moulds that are conservatively designed, which means they are composed fully of solid material. However, AM permits hollowing out the core of the part for reasons of lightweight design and thus minimises manufacturing time as well as material consumption. A major limitation to this process is the loss in stiffness, which can lead to a part's inability to withstand loads in subsequent manufacturing processes. [4]

2. Challenges in AM-generated CFRP moulds

The potential and limitations of AM-generated CFRP laminating moulds as rapid tooling moulds remain to be more clearly defined. In our previous case study [4], the potential towards zero waste in the additive manufacturing of such moulds was proven. However, that investigation focused on meeting manufacturing loads by vacuum bag moulding [5] and therefore only a manufacturing load of 1 bar ambient pressure was investigated. In conclusion, those results are not transferable to other common CFRP-manufacturing processes as they do not reflect load variation, e.g., in temperature and pressure. The present investigation will add to our earlier results, taking into account the manufacturing loads caused by an autoclave [7] during CFRP manufacturing. The main criteria investigated in this study, in contrast to the previous study, are:

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- temperature over the ambient,
- surrounding pressure loads higher than 1 bar,
  (both temperature and pressure loads arising from the conditions inside an autoclave)
- and a common but heat-resistant AM-material,

besides the differences in the geometry of the test body [4,6], see Table 1.

Table 1. Comparison of investigation criteria.

criteria	Galantucci et al. [6]	Lušić et al. [4]	this work
load type	swaging	surrounding pressure	surrounding pressure
value of load	until reaching failure load	one atmospheric load = 1bar	several loads given by an autoclave
material	Polycarbonate by *Stratasys*	ABS-M30 by *Stratasys*	ULTEM^{TM} 1010 by *Stratasys*
AM technology	fused deposition modeling	fused deposition modeling	fused deposition modeling
geometry	cylinder	twisted block	symmetric block
internal geometry	solid vs several narrow-waisted	solid material vs hollowed vs cross vs honeycomb structure	solid material vs hollowed vs cross vs honeycomb structure
temperature	not specified	not specified	non-steady-state, over ambient

3. Model concept, constraints, and target values

The model is based on an application scenario using an autoclave [7] for manufacturing carbon fibre reinforced plastics. So, the following boundary conditions were determined for this parameter study (Fig. 1):

- Ambient temperature: 20 °C to 120 °C. The heat transfer behaviour between the ambient air and the test body is not considered since we focused on deformation behaviour during heat conduction within the rapid tooling mould. Thus, the temperature is assumed to be directly acting on the component's surface.
- Ambient pressure: 1 to p bar, whereby p varies by increments of 0.5 bar up to p = 3bar = p_{max}.
- Time: ambient temperature and pressure are not stationary over time to reflect the process within an autoclave.

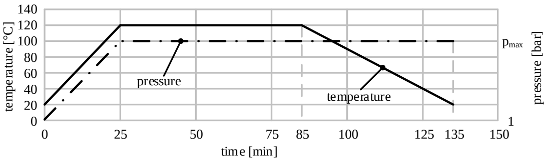

Fig. 1. Profile of temperature and pressure used in this parameter study.

The material used is ULTEM^{TM} 1010 (yield strength = 81 MPa, elastic modulus = 3.5 x 10³ MPa, coefficient of thermal expansion = 47 µm/(m°·C)). Since the mould is located in practice on a base (e.g., on a pin-type mould [8] or on a workbench), the ambient pressure p is exerted on its visible surface, see Fig. 2, but not on its base surface. Thus, the nodes of the finite elements within the base surface cannot move vertically, but can move horizontally.

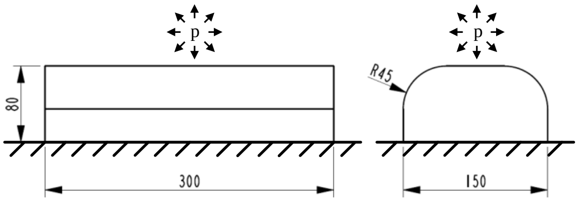

Fig. 2. Ambient pressure on rapid tooling mould (test body with nominal dimensions in mm).

In the same manner as described in [4], stair stepping or anisotropic material properties common in AM are not considered here. The target values for this investigation are:

- maximum total deformation[1],
- manufacturing time, and
- material consumption.

4. Experimental procedure

This section addresses the experimental procedure using finite element analysis. The following test bodies were stressed with temperature and pressure according to Fig. 1:

- Firstly (section 4.1), a solid design was used, which reflects reference values for deformation, manufacturing time, and material consumption.
- Secondly (section 4.2), the test body becomes a shell by hollowing out its inner core.
- Thirdly (section 4.3), an inner structure is simulated in two ways: once as a cross structure and once as a honeycomb structure.

The test bodies described in sections 4.2 and 4.3 serve to reduce manufacturing time and material consumption while maintaining the maximum deformation values from the solid design.

4.1. Determining reference values for the solid material

The maximum total deformation values for the different pressure levels was about 0.28 mm directed outwards and was reached in all cases at 120°C. In all other cases (shell design, cross-structure design, and honeycomb design, see sections 4.2, 4.3.1, and 4.3.2), the deformation was directed towards the body centre[2]. With an increase in pressure the deformation increases, but not to a large extent. The maximum equivalent

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[1] the equivalent stress is continually checked to confirm that it remains below the yield strength of Ultem^{TM}1010.

[2] Keeping in mind that the stress is caused by combining temperature and (over)pressure resulting in a deformation decrease by increased pressure.