Residual Stress Mitigation in Additively Manufactured Thick Composites

Francesco Taddei[1,2]*, Giacomo Struzziero[1], Véronique Michaud[2]

[1]Empa, Laboratory for Mechanical Systems Engineering, Dübendorf, Switzerland

[2]EPFL, Laboratory for Processing of Advanced Composites, Lausanne, Switzerland

**francesco.taddei@empa.ch*

Empa Materials Science and Technology

EPFL

Introduction

The exothermic nature of the cure reaction causes a temperature overshoot and an inhomogeneous temperature distribution during the manufacturing of carbon-fibre reinforced polymers (CFRP). This leads to uneven thermal expansion and chemical shrinkage within the component, generating cure-induced residual stresses which are often source of shape distortions, matrix microcracking, and drop in mechanical and fatigue performance [1]. The temperature gradients through the component are more pronounced in thick-section composites, which are being increasingly employed in several sectors such as wind energy, aerospace, chemical, petrochemical, marine, military, and gas transportation. Such process-induced defects might also increase the number of rejected parts, affecting both production costs and process sustainability.

A technique with the potential for mitigating the exothermic overshoot and the generation of cure-induced stresses and strains consists in depositing additively the material while it is being partially cured and after it has been possibly pre-cured [2-4]. This study investigates this new processing strategy, comparing the residual stresses and temperature profile developed during standard curing and additive curing through numerical simulations. The role of the pre-cure level, the final cure temperature and the deposition speed are discussed.

Material and method

Epoxy resin characterisation → **input in** → **Finite Element Model (Coupled thermo-mechanical analysis)**

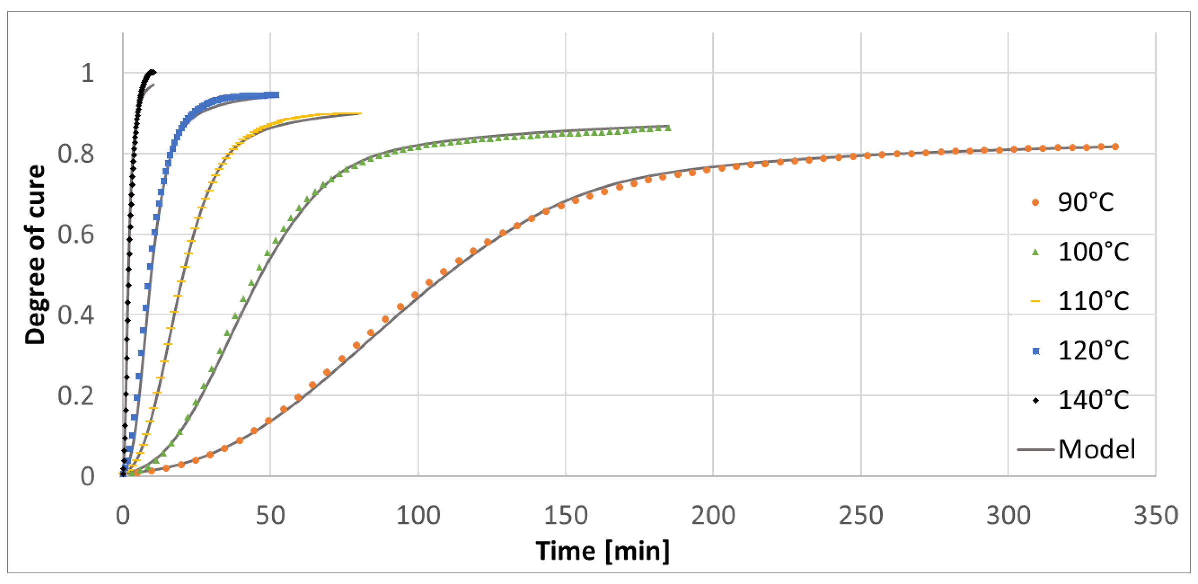


Fig. 1: *Degree of cure in function of curing time and temperature (cure kinetics)*

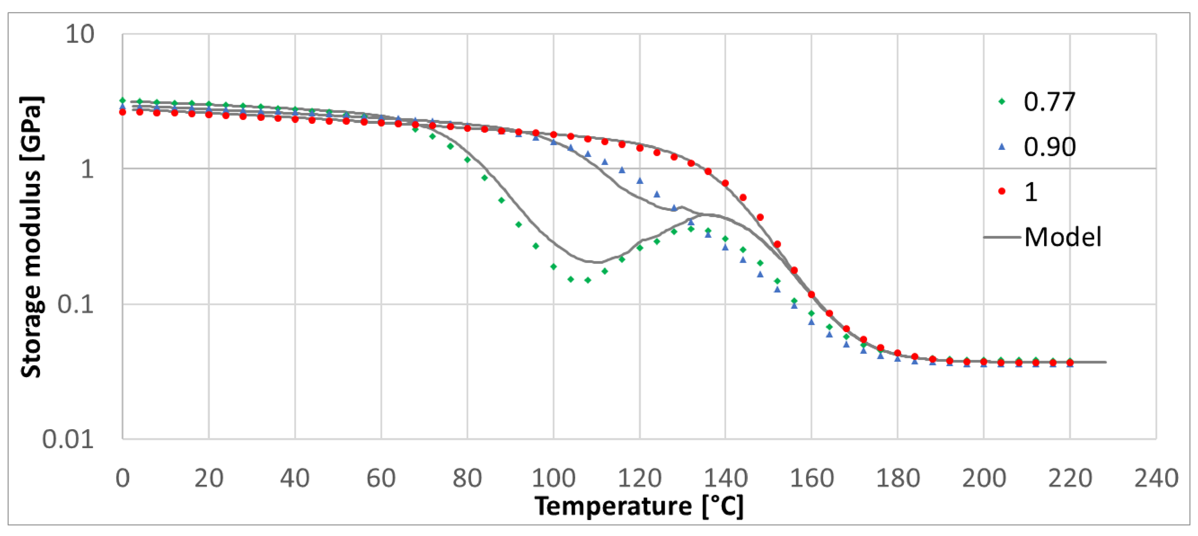
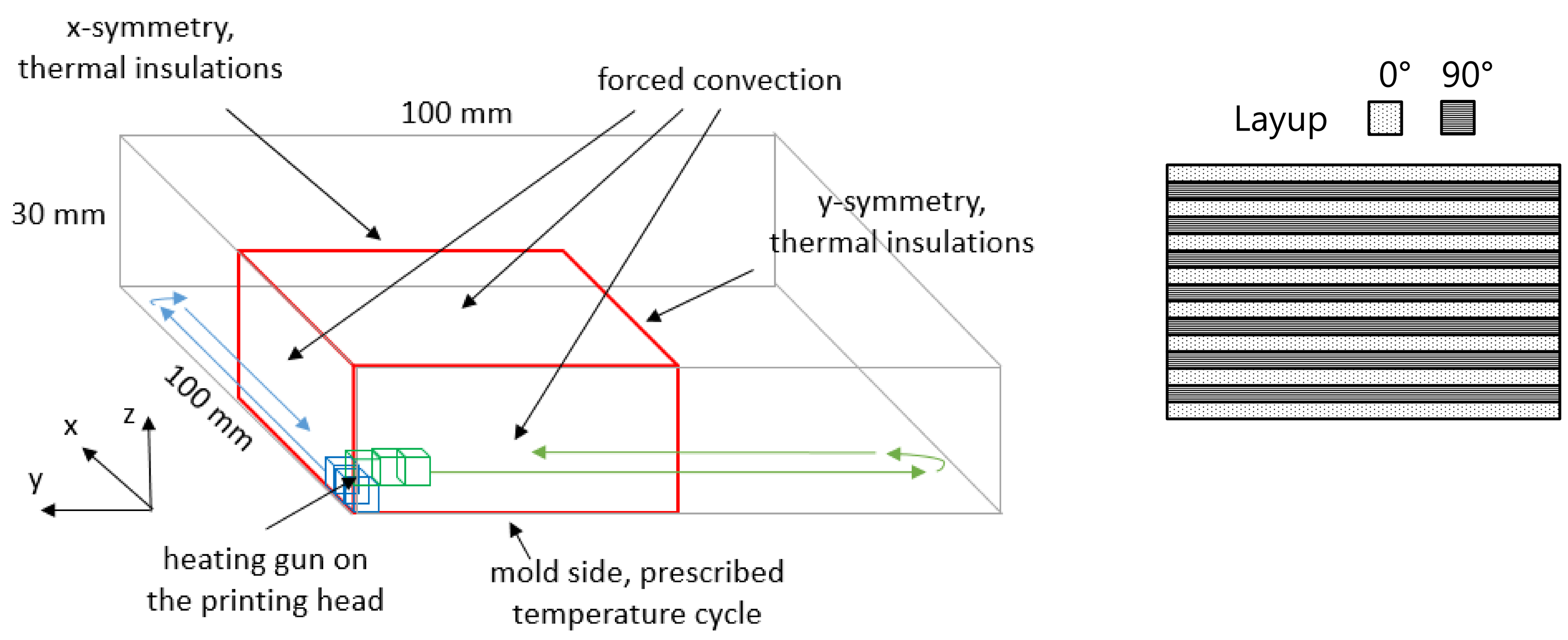


Fig. 2: *Storage modulus of the resin in function of degree of cure and temperature*



User-defined subroutines:

- SDVINI, DISP, FILM (initial and boundary conditions)
- UMAT, UMATHT (material properties, heat transfer and micro-mechanics equations)
- UEPACTIVATIONVOL (progressive activation of elements)

Outputs:

- Temperature and degree of cure
- Stresses and strains

Fixed parameters:

- Deposition temperature (80°C)
- Heating/cooling rate (1°C/min)
- Convection coefficient (50 W/m^2/K)

Variable parameters:

- Level of pre-cure (0.02, 0.1, 0.2, 0.3)
- Final cure temperature (120°C, 130°C)
- Printing speed (300 mm/min, 600mm/min)

Results

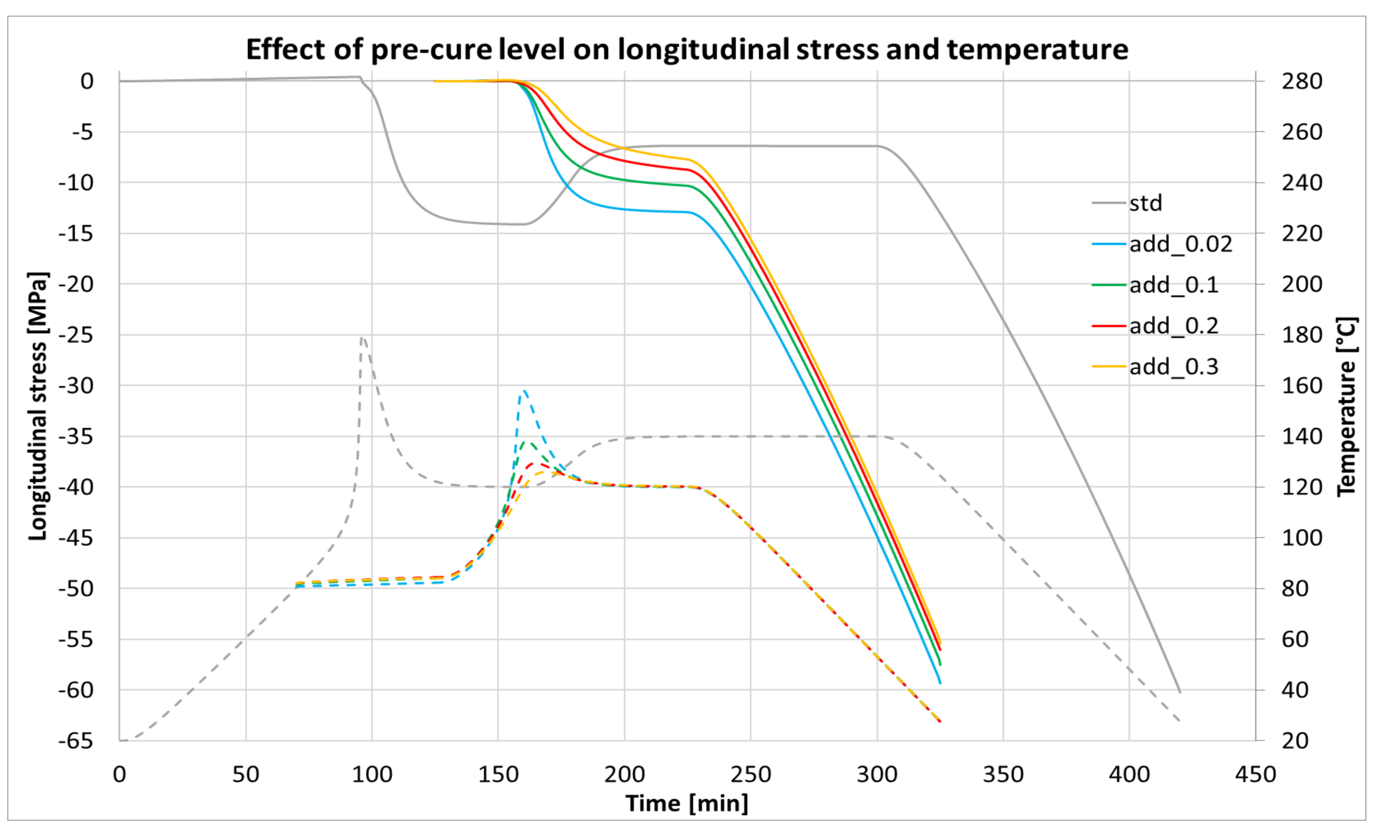


Fig. 3: *Residual stress (continuous lines) and temperature evolution (dashed lines) during standard and additive manufacturing with different levels of pre-cure*

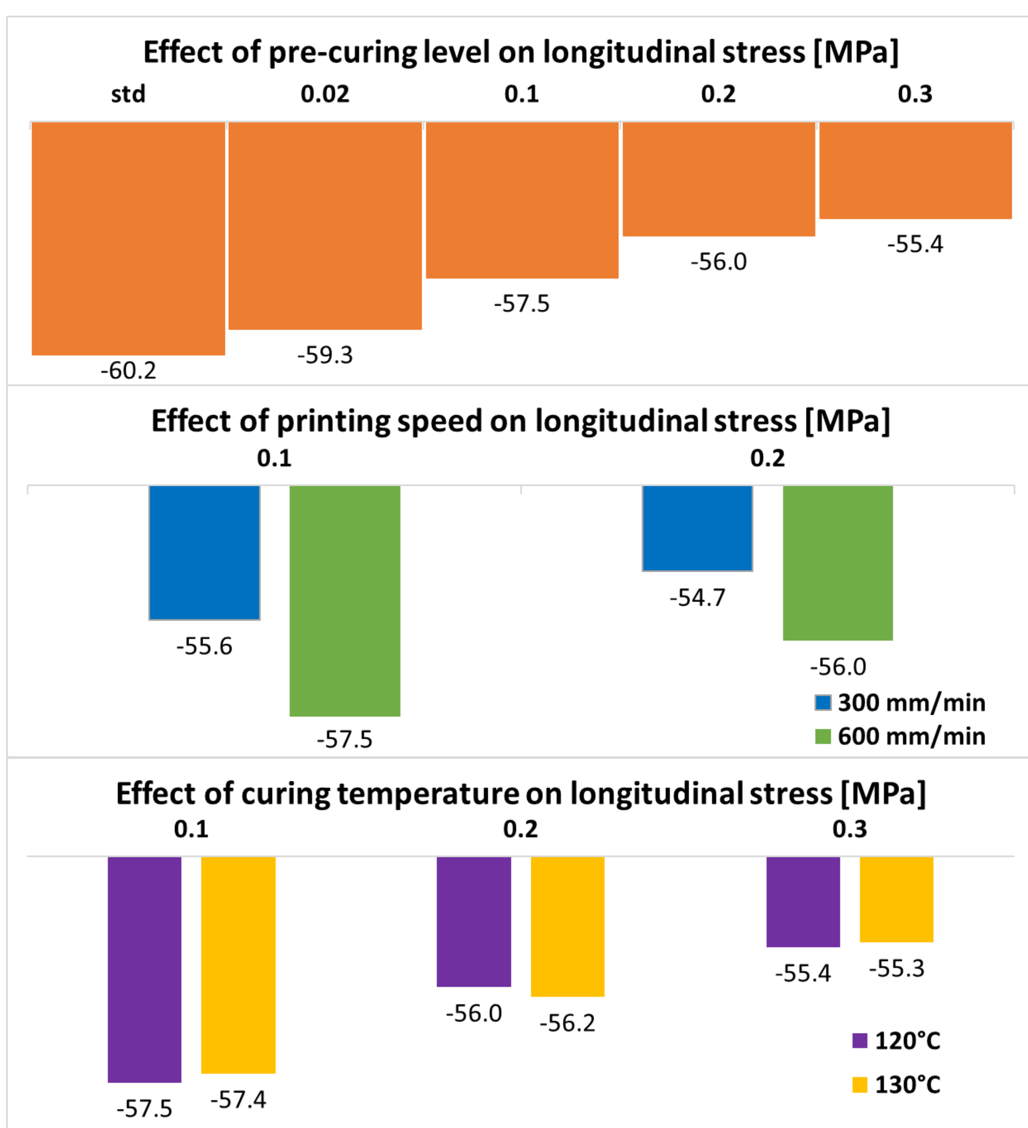


Fig. 4: *Role of process parameters on longitudinal stress*

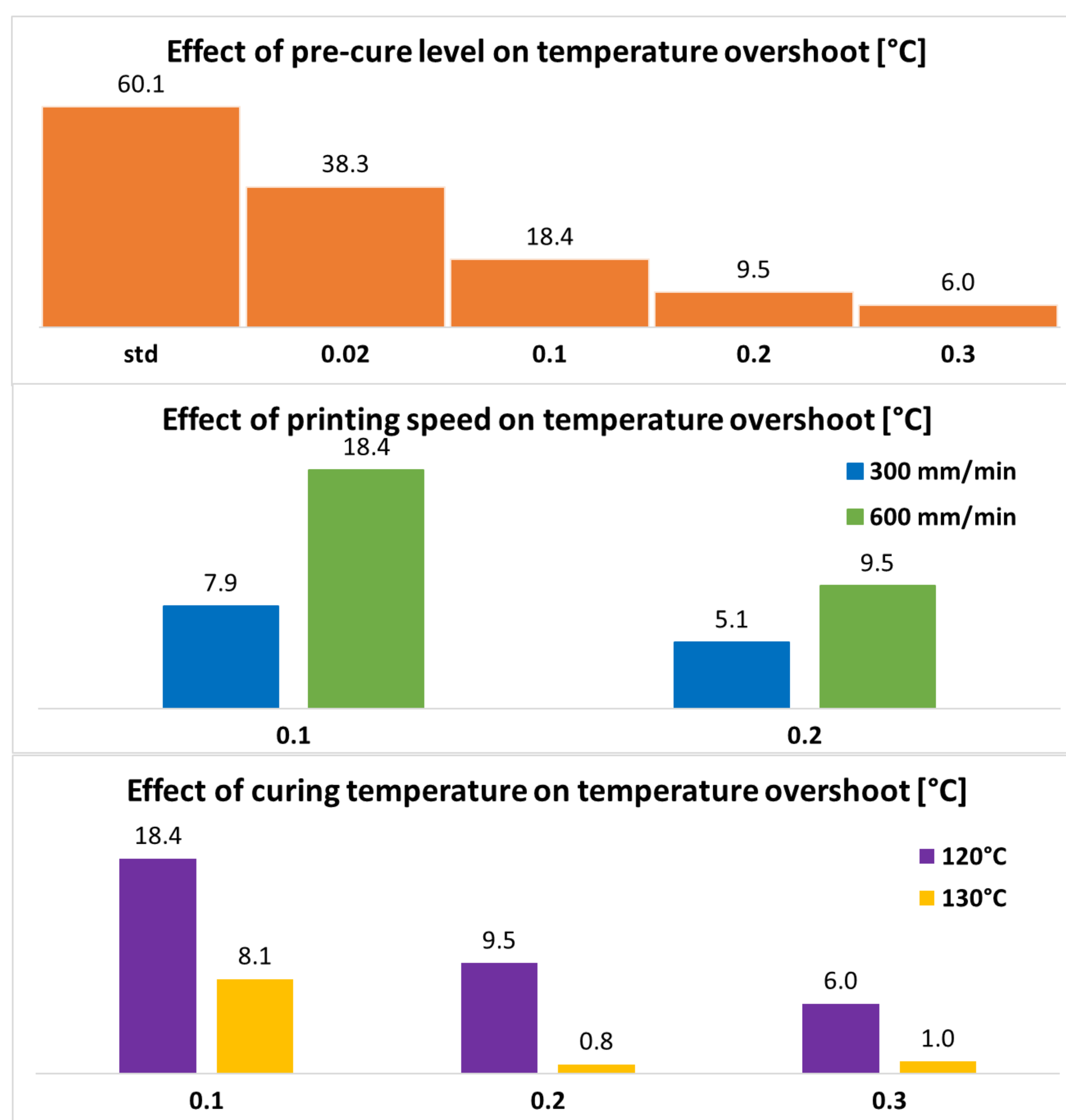


Fig. 5: *Role of process parameters on temperature overshoot*

Conclusions and outlook

Pre-curing the carbon/epoxy filament before deposition and partially curing it before final cure lead to a reduction in temperature overshoot and residual stresses inside the laminate. This effect is particularly marked for thick laminates. The exothermic phenomenon during the final cure is milder because a portion of the reaction energy has been exhausted during the partial cure. Consequently, the lower temperature translates into a smoother cure, mitigating the generation of cure-induced stresses that are developed when the material has exceeded its gelation point.

Future investigations should address the limits in the degree of partial cure since the viscosity of the polymer should not exceed values that would prevent a good consolidation and adhesion between the tows. Finally, the emergence of deposition defects when processing the partially cured material needs to be evaluated.

- The **partial curing** of the component while it is being built up additively reduces the temperature overshoot by *36%* and the cure-induced stresses in longitudinal direction by *2%*.
- The introduction of a **pre-curing** stage up to 0.3 degree of cure further mitigates the exothermic overshoot by *90%* and the longitudinal residual stresses by *8%*. Moreover, the stress gradient through the thickness is decreased by *45%*.
- The use of a lower **deposition speed** has a beneficial effect; it acts similarly to the pre-cure, allowing to reach a higher partial cure before the final cure cycle.
- The use of higher **curing temperature** does not show a significant effect for the studied values.

References:

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