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# Multiphysics Modeling of VAT Photopolymerization for Additive Manufacturing of Ceramics

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Additive manufacturing (AM) of ceramics is considered a potential breakthrough technique considering the added design freedom that can not be achieved using conventional production techniques. The current state-of-the-art facilitates accurate fabrication of complex, small and most importantly, thin walled structures, such as micro reactors [4]. However, the production of large-scale technical ceramics with thick walled structures remains challenging.

The focus in this contribution lies on the indirect process of fabricating a ceramic (near) net shaped product through a so-called 'green' intermediate phase using VAT photopolymerization, i.e. stereolithography. Starting from a three-dimensional computer model, a repetitive process of depositing a layer of 'slurry' consisting of monomer, photoinitiator and ceramic particles, and selective illumination by UV light ultimately results in the complete green phase product. In a subsequent heating step the polymer, i.e. the solidified or cured monomer, is debonded and the ceramic particles are sintered together into an ideally fully dense final product [2]. This process is illustrated in Figure 1. Although the latter two process steps, i.e. the green part post processing steps, are crucial in developing the intended ceramic product, the focus lies on the printing process itself.

In order to obtain a better understanding of relevant phenomena and key parameters in the printing process a numerical approach is used. From a modeling point of view, the entire process is of a highly multi-physical nature. The deposition of the viscous fluid layer with dispersed particles requires a rheological model. The subsequent illumination through the layer of slurry is a physics problem, even more eminent due to the light scattering induced by the ceramic particles [2]. The consequential polymer

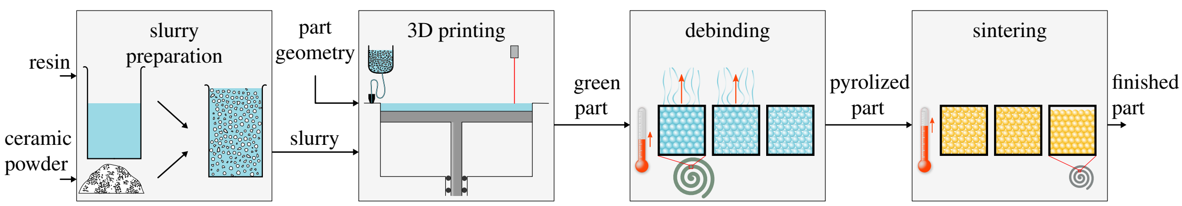


Figure 1: Abstract overview of the ceramic production process.

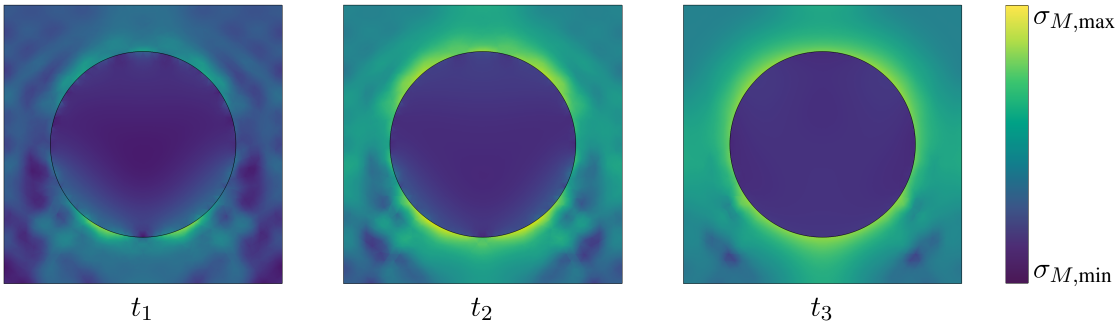


Figure 2: Illustration of the inhomogeneous evolution of the Von Mises stress during polymerization as a result from light scattering by a ceramic spherical inclusion.

curing process poses a chemical one, in which the exothermic reaction generates heat [1]. Finally, a degree of conversion dependence is required in a mechanical model to relate to e.g. viscosity, chemical shrinkage, thermal expansion and internal stress.

The proposed finite element model assumes a quasi-static situation, i.e. ignoring the layer deposition process. Due to the small difference between the particle dimensions and the wavelength of the light an electromagnetic wave description is required for the light propagation. A clear separation in time-scales is introduced by solving the response to the monochromatic laser light in the frequency domain. It should be noted that this electromagnetic wave assumption also allows for reproducing the typical Beer-Lambert like attenuation of light in an unfilled system [3] or photobleaching of the initiator. The local light intensity is then coupled to cure kinetics, which in turn induce a time-dependent increase in temperature, primarily due to reaction heat, and an evolution of mechanical properties. From here the influence of different model parameters on effects ranging from light propagation, degree-of-cure profiles to resulting stresses can be examined. An example of the latter is depicted in Figure 2, where the stress evolution during polymerization around a single ceramic particle is illustrated. In this particular case the 1 $\mu$m particle is subjected to UV light. The effect of particle arrangement on the degree of conversion and internal stress is investigated using this coupled modeling approach.

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