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TITLE: Development of a fluid dynamic model of bead deposition in additive material extrusion

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ABSTRACT:

Material extrusion (MEX) is an additive manufacturing process in which material, typically a molten thermoplastic polymer, is extruded through a nozzle onto a build plate, where it cools and solidifies. The desired geometry is built up by stacking layers, each made up of beads of extruded material. The process allows for the flexible construction of complex near net shapes without specific tooling. Feedstocks other than pure polymers may be used as well, particularly fibre reinforced thermoplastics or thermoplastics filled with ceramic, glass, or metallic particles. In the latter case successive debinding and sintering steps can be added to the process chain to obtain finished ceramic, glass, or metallic parts respectively. Parts created using MEX comprise a *mesostructure* consisting of individual beads fused to one another and air-filled voids. The mechanical properties are therefore reduced compared to the monolithic material. Especially part strength is determined by the bonds formed at the interfaces between beads [1]. The success of subsequent binding and sintering steps also requires minimal void content and sufficient adhesion between beads. However, the mesostructure is specific to the given printing parameters, feedstock composition, and environmental conditions. Determining the resulting mesostructure for all relevant combinations within the extensive parameter space experimentally would be prohibitively laborious. Therefore, various numerical models of the bead deposition have been proposed. Usually either the arbitrary Lagrangian-Eulerian (ALE) method based on finite elements (FE) [2], the finite volume method (FVM) [3], or the smoothed particle hydrodynamics (SPH) method [4,5] are used. The SPH method seems particularly well suited for the given problem, as it can be easily applied to any nozzle trajectory due to its mesh-free approach. Furthermore, it intrinsically captures the evolution of arbitrarily complex surfaces. Like the ALE method, it lends itself well to the implementation of a solidification mechanism, due to its Lagrangian frame of reference. However, existing models are very limited in their scope, miss important components such as a thermal model, or any form of solidification.

This work presents a new fluid dynamic model of the deposition process using the free and open source SPH-framework *SPlisHSPlasH* [6]. Figure 1 shows the extrusion of a single bead. The model comprises a movable particle inlet representing the nozzle through which particles enter the initially empty domain. The particles' initial velocity is determined by a quadratic profile over the inlet's cross section. The nozzle's movement is determined by a time-accurate interpretation of the G-code provided by the open source package *pyG-CodeDecode* [7].

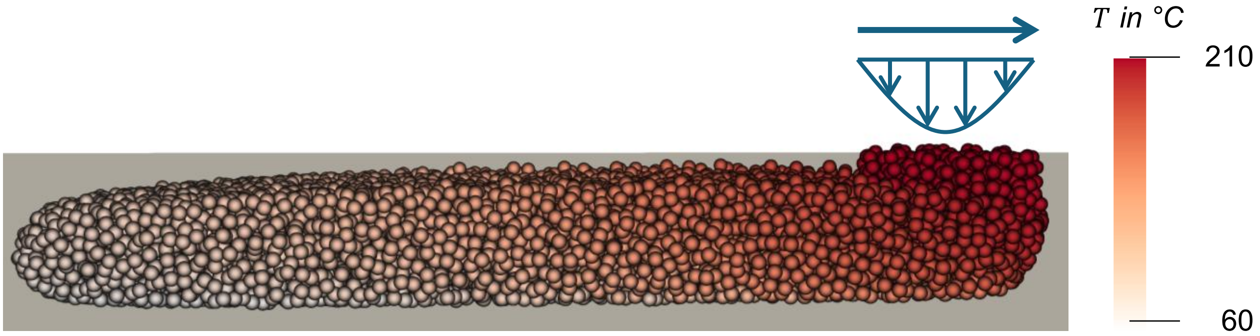

Figure 1: Extrusion of a single bead. Particles are coloured according to their temperature.

The model includes a thermal balance equation. Particles enter the domain with the preset extrusion temperature and cool down due to conductive heat exchange with the build plate as well as convective and radiative heat exchange with the environment. The thermal model enables the use of temperature-dependent material properties such as viscosity determined by the Cross-Williams-Landel-Ferry (CWLF) equation.

The model is applied to various test cases to verify that it can reproduce common geometries within a part. These include stacks of beads, tight angles, bridges, and solid as well as patterned infill. The work demonstrates challenges in determining thermal and mechanical boundary conditions as well as in representing melt solidification by artificially freezing particles. Finally, a surface reconstruction based on the numerical results is compared to CT-scans of stacked deposited beads to determine the model's ability to accurately capture the resulting bead shape. An example of a surface reconstruction and a CT-scan are shown in Figure 2 (a) and (b) respectively. Preliminary results show that the chosen simulation technique should be well suited to predict small mesostructures when artificial particle freezing is used while a purely viscous material model is insufficient.

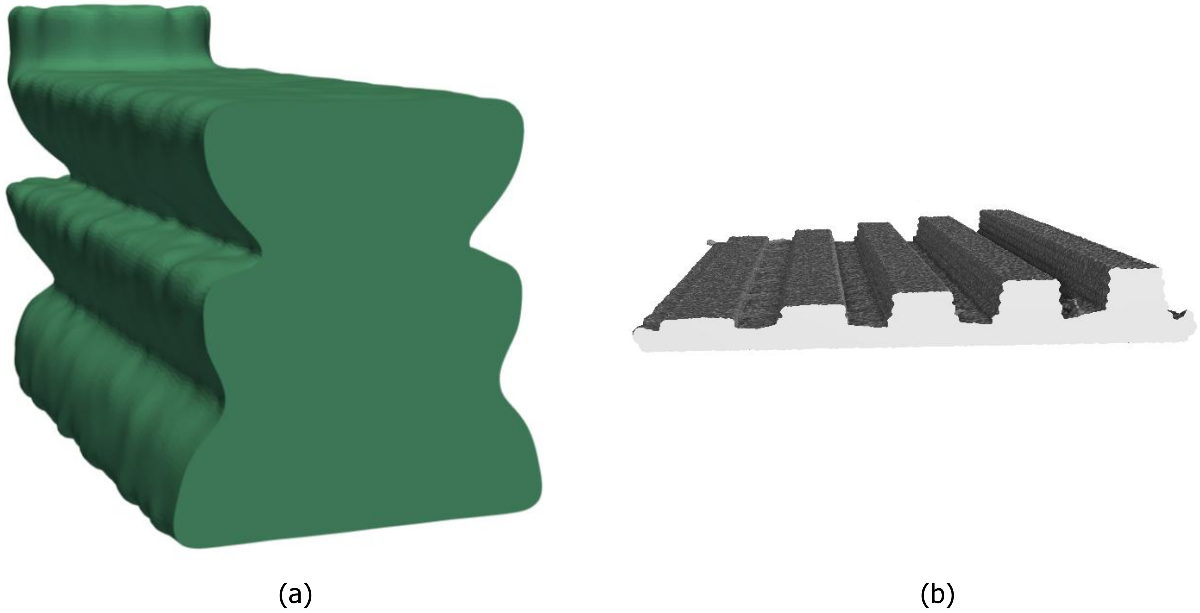

Figure 2: (a) Clip through a surface reconstruction from a simulation result using splashsurf [8]. (b) CT-scan of stacked beads for validation.

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