

A thermo-mechanical Particle Finite Element Method for unified fluid-solid formulation: application to phase change and metal additive manufacturing

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Abstract

Metal Additive Manufacturing (MAM) processes are characterized by highly localized heat inputs, steep thermal gradients, rapid phase transitions, and evolving interfaces. Numerical simulation of MAM processes is particularly challenging due to the multiphysics nature of these phenomena. The aim of this contribution, is to present a single robust numerical framework based on the Particle Finite Element Method (PFEM) capable of simulating a wide range of 2D and 3D applications in both fluid and solid mechanics, including fluid-structure interaction, phase change and MAM. Our original contribution lies in the combination and adaptation of state-of-the-art developments from the PFEM literature, including fluid-solid coupling, second-order accurate time integration schemes, advanced remeshing techniques, phase transformation models and laser-material interaction. Our PFEM formulation is unified and monolithic since the same conservation equations (momentum balance, mass conservation and heat equations) and nodal unknowns (velocity, pressure and temperature) are used in a single global system of equations to solve the fluid and solid parts. Solid materials are represented using a thermo-elastic-viscoplastic model

(hypoelastic formulation) while fluid materials are represented using a general non-Newtonian fluid model. A phase transformation model allowing continuity of the deviatoric stresses across the whole mushy zone is presented. To properly model the thermo-mechanical couplings, an expression of the thermal expansion coefficient including a pressure-dependent term, which is usually not taken into account, is derived. Moreover, the generalized- α time integration scheme is adapted to our unified formulation. All three conservation equations are discretized and integrated using the same scheme and a single set of integration parameters. The problem is solved using the finite element method within the Lagrangian framework and large deformations of fluids and solids are addressed using a remeshing procedure, which is the underlying principle of the PFEM. The proposed formulation is extensively verified using simple benchmarks from the literature and it is then applied to more complex problems to show the capabilities of the method in the context of MAM.

Keywords:

PFEM - Particle Finite Element Method Additive Manufacturing Phase change Unified fluid-solid formulation Thermomechanics