Laser polishing - numerical modelling using a mesh-free incompressible SPH method

EPSRC Centre for Innovative Manufacturing in LASER-BASED PRODUCTION PROCESSES

Odin du Plessis*[1], Wojciech S. Gora[1], Marcus Ardron[3], Yeaw Chu Lee[1], Duncan P. Hand[1]
[1] Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK
[2] School of Materials, The University of Manchester, Manchester M13 9PL, UK
[3] Renishaw plc, Research Park North, Riccarton, Edinburgh EH14 4AP, UK

Introduction

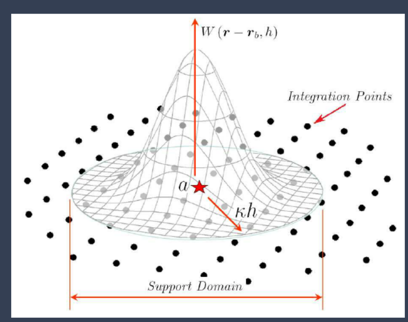
- The laser polishing process leads to local melting (50-100μm) of surface and subsequent re-solidification in a smoother state.
- A feasibility study is pursued in order to model the laser polishing of stainless steel using Smoothed Particle Hydrodynamics; a novel mesh-less numerical method will enable deeper analysis of phenomena and inexpensive virtual testing.
- Incorporating a wide range of physical phenomena including surface tension, Marangoni forces, thermal conduction;phase change and latent heat.

Motivation

- Experimental prototyping aims to improve final surface quality of additively manufactured (AM) structures.
- The laser polishing process is based on melting and subsequent solidification of a micro-layer of material, using a scanning laser beam as the heat source for a smooth topography may be expensive in material acquisition, processing time and rapid measurement ability.
- A mature, efficient and accurate multi-physics code is desirable to interpret experimental results, reveal novel physical mechanisms and save on mentioned costs.

SPH-Methodology

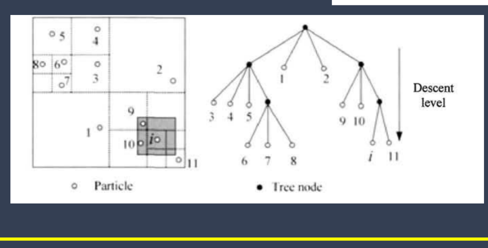
- Lagrangian particle method using a kernel and its derivatives to discretise continuum equations. Particle nature renders re-meshing unnecessary; high distortion not penalised.
- Standard weakly compressible SPH (WCSPH) based on sound speed with Pressure-density equation of state; small time-steps required, noisy pressure possible.
- Tensile/compressive instability requires corrective terms.
- Kd-tree nearest neighbour algorithm implemented.



kernel and support range.

ISPH

- Incompressible SPH (ISPH) with Pressure-Poisson equation solver. Implemented for density invariant flows.
- Faster and more accurate than WCSPH though higher memory overhead required.



Multi-dimensional kd-tree

Numeric Framework

Heat Boundary Conditions and material Model:

- (Distant) Thermal boundary condition enabled contracting of problem domain
- Internal energy, latent heat and melting
- Laser profile: Gaussian external source
- - exponential decay into substrate

$$h=\begin{cases} c_s T & solid: T<T_s \\ c_s T_s + c_{in}(T-T_s) & part-melt: T_s \leqslant T \leqslant T_l \\ c_s T_s + c_{in}(T_l - T_s) + c_l(T-T_l) & liquid: T>T_l \end{cases}$$

$$\dot{h}=c_v \dot{T}$$

$$T_i = T_b + x_{ib}\frac{\Delta T_{ib}}{\Delta x_{ib}}$$

Fluid Model:

- Full Navier-Stokes equations
- Continuum Surface Force (CSF) macroscopic model formulated for single phases
- Corrective-SPH (CSPH) gradients for free surfaces.

$$\nabla \boldsymbol{U}^* = \nabla\left\{\frac{\nabla P}{\rho}\right\}\Delta t$$

$$\rho \ddot{x}_i = -\nabla P + \mu \nabla^2 \boldsymbol{U} + \delta_\epsilon\left\{\gamma \kappa \hat{\boldsymbol{n}} + \nabla \gamma . \hat{\boldsymbol{t}}\right\} + \boldsymbol{F_b}$$

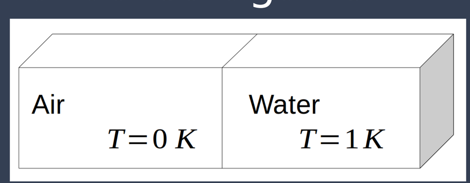
Thermal effects

Discontinuous thermal conduction rod test

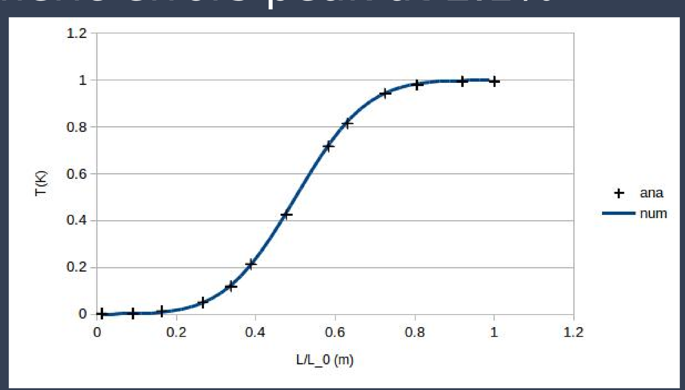
Full and free surface modelling of thermal conduction, validated against analytic (erf) function for a cooling bar:

I. Continuous bar
II. Discontinuous bar with ratios: ρ=1000:1.2, κ=0.62:0.0254, c=4.19:1.01

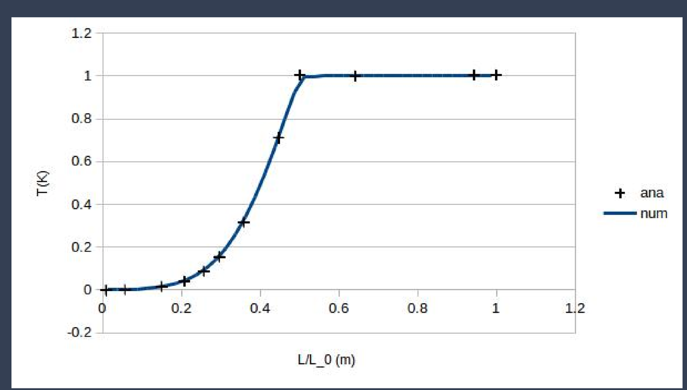
Numeric errors peak at 2.1%



Numeric setup:



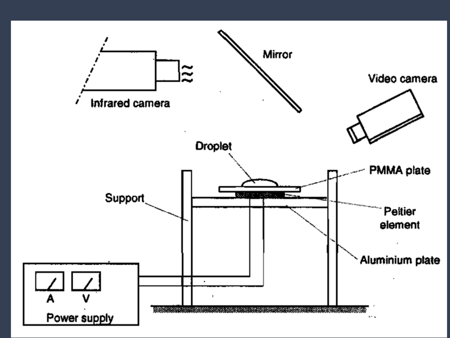
Continuous materials t=10s.



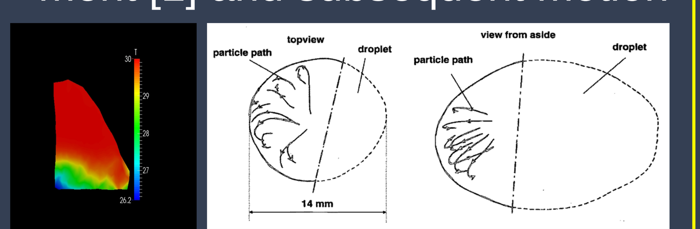
Discontinuous materials t=10s.

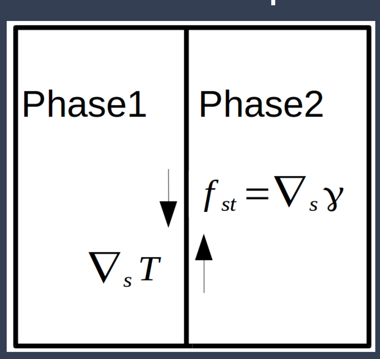
Marangoni Discretisation

- Component of surface tension normal to the surface arises through gradients of surface tension caused by chemical (e.g. soapy water, coffee stains) or thermal (e.g. thermo-capillary convection) anisotropy.
- Marangoni force validated for interface, normal to thermal gradient
- Force Convergence Test performed along interface for both curvature and stress divergence surface tension methods. Results show good agreement between analytic and numeric quantities.

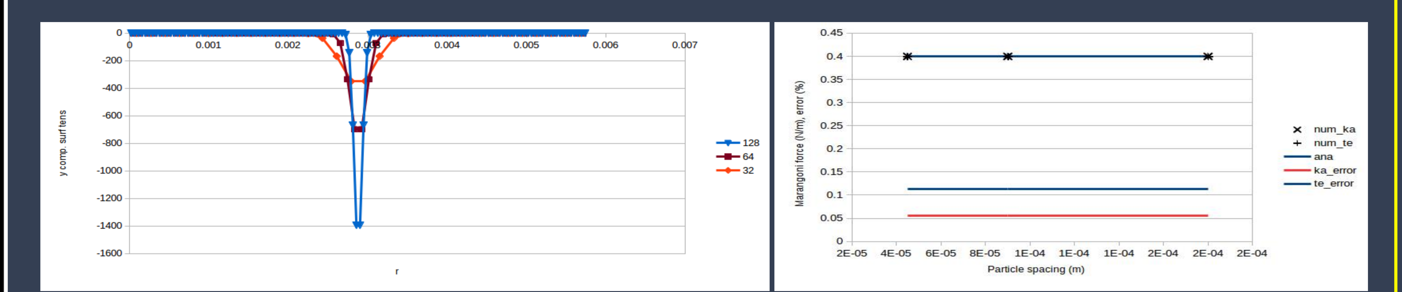


Thermocapillary droplet experiment [1] and subsequent motion





Numeric setup:

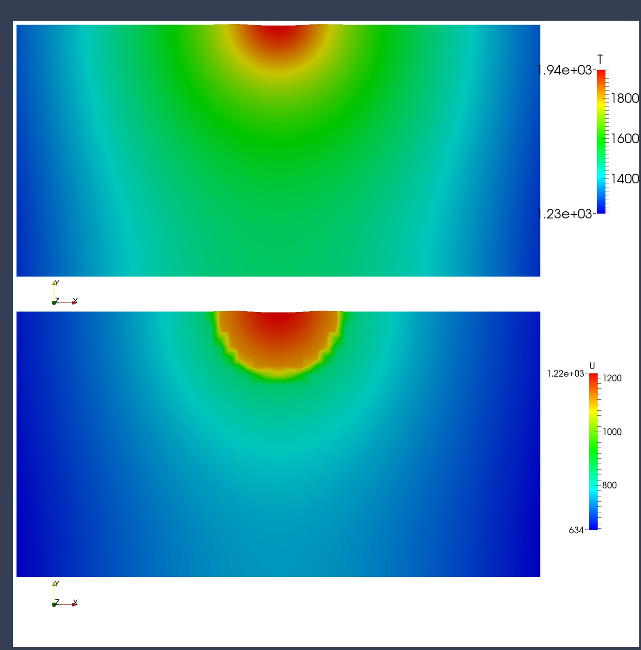


Convergence test for 32^2,64^2,128^2 particle grids

Spot beam melting/re-solidification

Stainless steel power/duration variance test

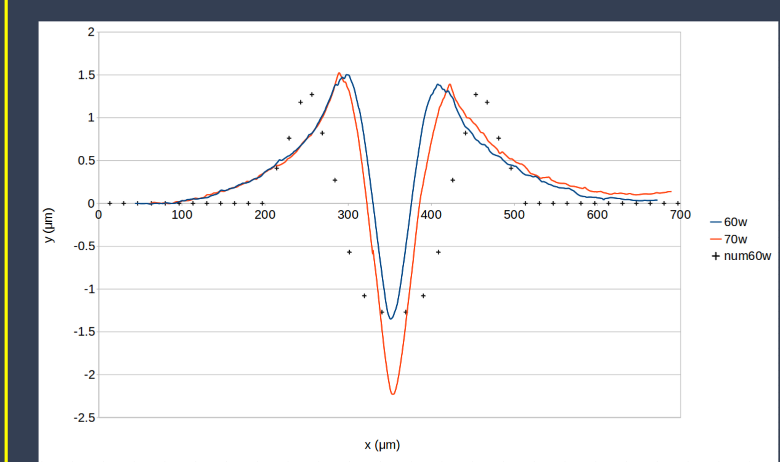
Spot beam for a varying beam duration and power SPI fibre laser



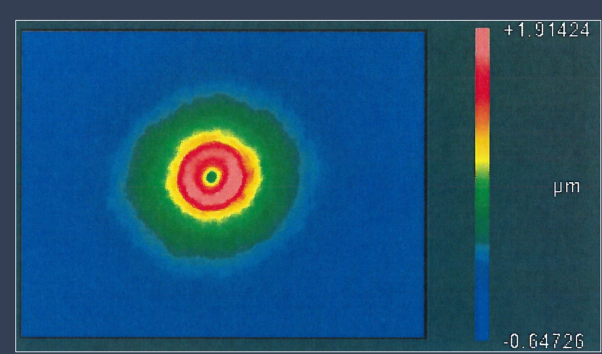
Temperature and Internal energy in the melt zone.

Laser properties:
- Beam radius: 40μm, angle 90°

Material properties:
- Dimensions: 500x500x300mm,
- Density: 8000kgm^{-3},
- Surface tension (air): 1.9Nm^{-1}
- Kinematic viscosity: 0.75μm^{2}s^{-1}
- Thermal conductivity: 16.3Wm^{-1}K^{-1},
- Thermal absorptivity: 0.3
- Specific heat fluid: 712 Jkg^{-1}K^{-1}
- Marangoni temp factor: -3.4e-4Nm^{-1}K^{-1}
- Latent heat: 247 kJkg^{-1}
- Liquidus, solidus temperature: 1697,1727K



Surface profile post-solidification



Experimental xy-data [2] (40W, 2.5ms).

Spot beam test varying laser duration and power.

- Power tests: 40, 50, 60, 70, 80, 90, 100W for 2ms
- Duration tests: 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20ms at 40W

Further developments

- 2d/3d beam spot tests ongoing.
- Different materials to include Cobalt-Chrome (CoCr), Titanium alloy (Ti6Al4V) testing
- Beam scanning tests to include scan angle and pattern variance.
- Material stress/thermal softening inclusion predicted to alleviate edge anomalies in beam spot tests.

Conclusions

- Numerical results show strong correlation to experimental post lasing surface scans.
- ISPH satisfies need for an efficient and effective modelling algorithm, capable of modelling the full set of physics required to simulate surface melts.

[1]. den Boer, A. W. J. P. (1996). Marangoni convection: numerical model and experiments. Eindhoven University of Technology.
[2]. Courtesy of Wojciech S. Gora, W.S.Gora@hw.ac.uk

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*od8@hw.ac.uk

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