Laser Heating and Melting of Metals on Nanoscale: Breakup of Metal Filaments

IHTC-17: ID 31

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Overview

We apply a previously-developed asymptotic model [1, 2] to instability and breakup of metal filaments of nanometric dimensions exposed to heating by laser pulses, and placed on thermally conductive substrates, see *Fig. 1*. One particular aspect of this setup is that the considered heating is volumetric, since the absorption length of the applied laser pulse is comparable to a typical filament thickness. In such a setup, absorption of thermal energy and filament evolution are coupled, and must be considered self-consistently. Our asymptotic model allows for significant simplification since it reduces a complicated problem involving Navier-Stokes equations coupled with heat transport. The presented computational results are obtained in the GPU computing environment, which allows for fully nonlinear time-dependent simulations in large three-dimensional computational domains.

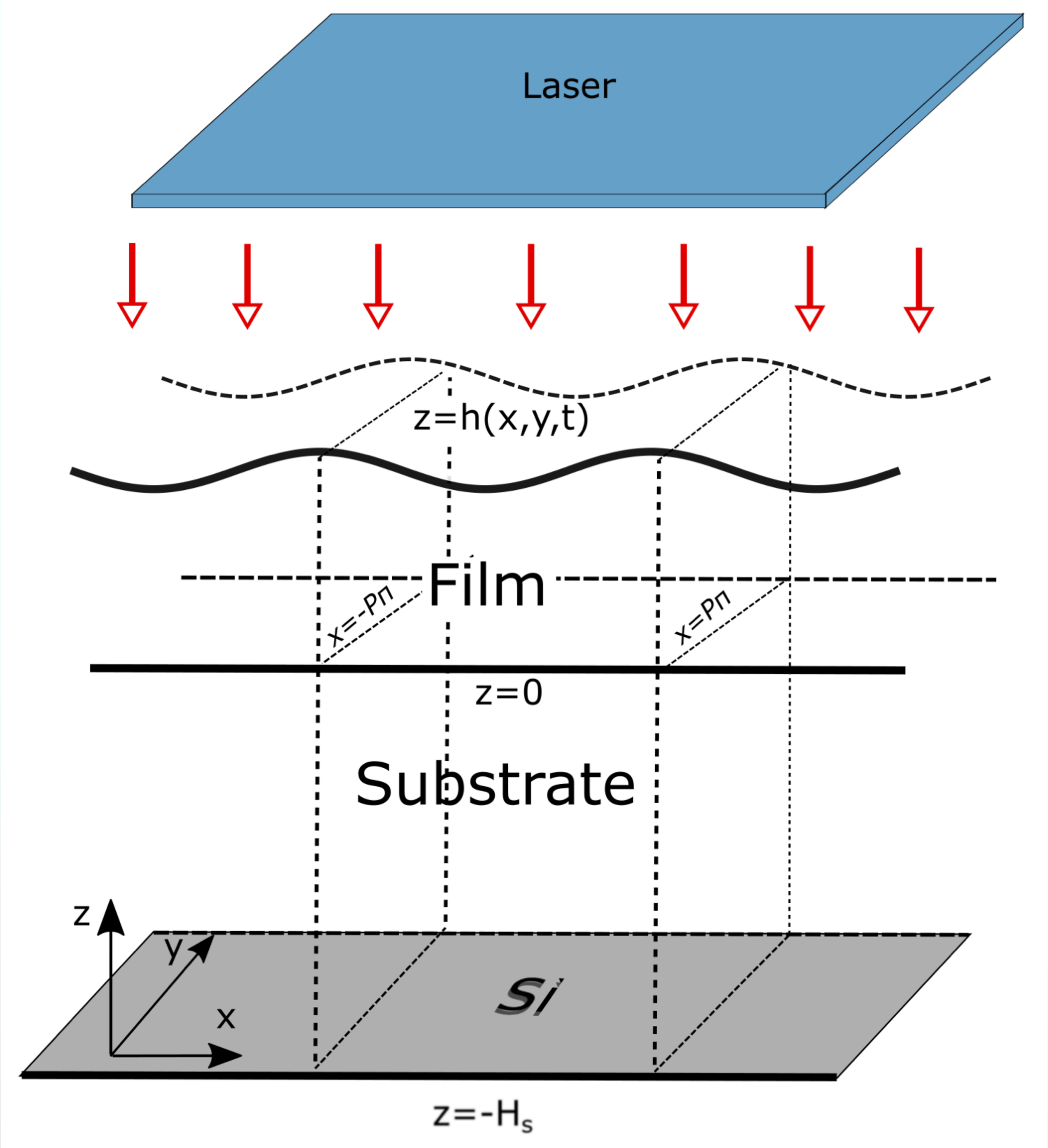

Fig. 1: Sketch of experimental setup, see [2].

Motivation

Self- and drected-assembly on nanoscale is important in a number of advanced contemporary applications, see [3] and references therein. Understanding relevant thermal transport mechanisms brings us a step closer to be able to use thermal effects to direct instability development.

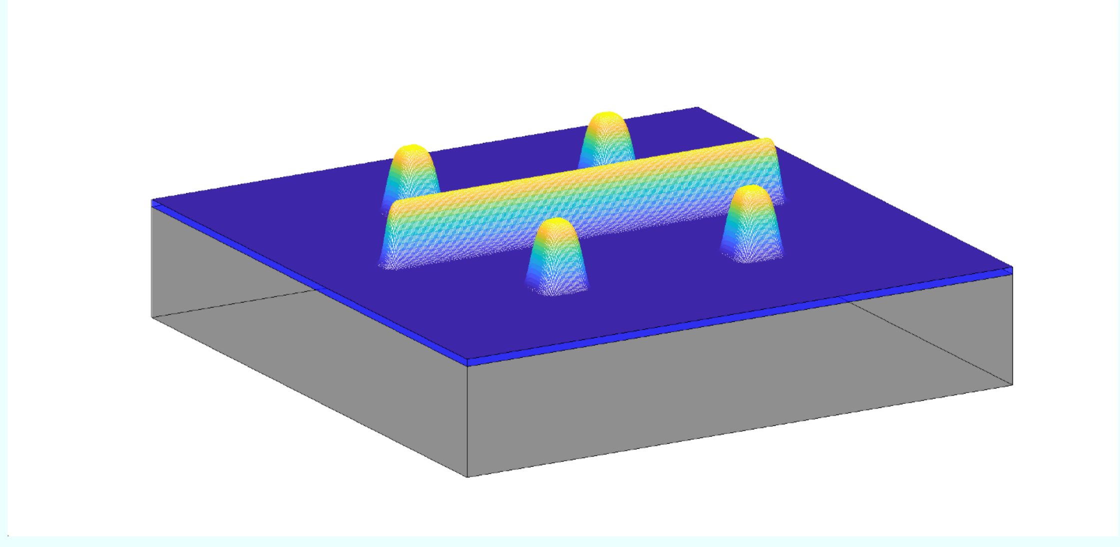

Fig. 2: Considered film geometry.

Main assumptions

- Metal film is of nanoscale (10 -20 nm thickness, see *Fig. 2* for the considered geometry.
- The absorption length for laser radiation is comparable to film thickness.
- The laser melts the metal film.
- While liquid, metal evolves as a Newtonian fluid with temperature-dependent material properties (viscosity, surface tension).
- Substrate itself is thin (100s of nm), and characterized by small thermal conductivity relative to the metal one.

Equations

Film:

$$\partial_t h + \nabla_2 \cdot \left[\frac{1}{\mu(T)}\left(h^3 \nabla_2\left(\Gamma \nabla_2^2 h + \Pi(h)\right) + h^2 \mathrm{Ma} \nabla_2 (\Delta T)\right)\right] = 0$$

h	film thickness	Γ	surface tension
μ	viscosity	Π	metal-substrate interaction
T	temperature	Ma	Marangoni number

Temperature:

$$\mathrm{Pe}\ h \partial_t T_\mathrm{f} = \nabla_2 \cdot (h \nabla_2 T_\mathrm{f}) - \mathcal{K}\left(\partial_z T_\mathrm{s}\right)|_{z=0} + h\overline{Q}$$

$\bar{Q}$ film-averaged source term

$$\overline{Q} = h^{-1} \int_0^h F(t)\left[1 - R(h)\right] \exp\left[-\alpha_\mathrm{f}(h - z)\right] dz$$

$F(t)$ time-dependent laser pulse

Simulations: GPU - based finite difference method; the code is in public domain, see [2].

Results

Main point: metal geometries communicate via thermally conductive substrate: larger metal volume leads to more energy absorption and faster evolution since viscosity decreases with temperature: `thermal crowding'. *Figures 3 - 5* show few examples of the pillar influence.

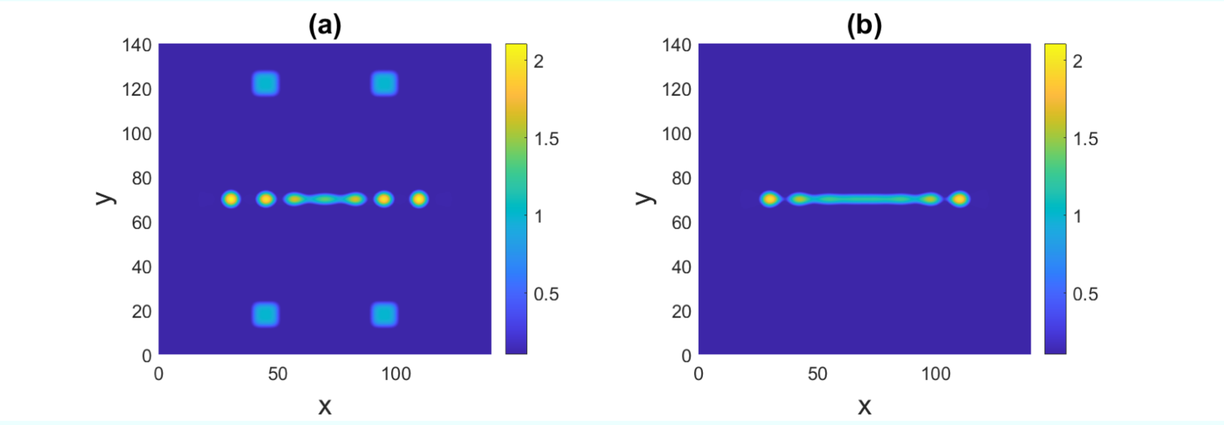

Fig. 3: Filament and pillars: evolution is faster if pillars are present.

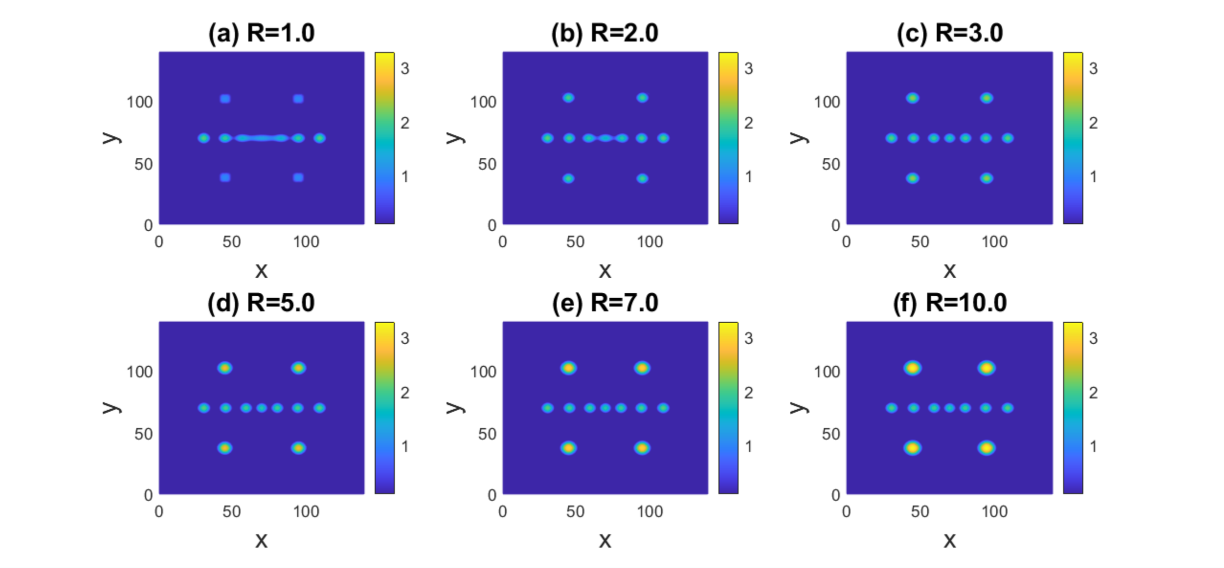

Fig. 4: Influence of pillar size: larger pillars lead to faster evolution.

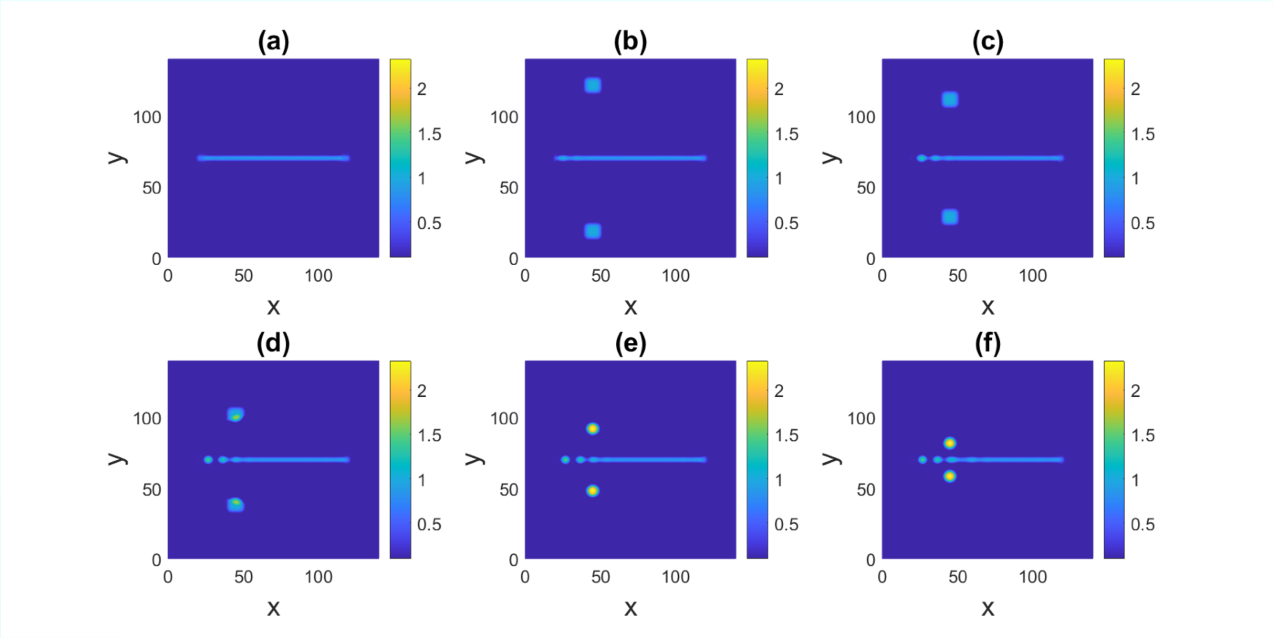

Fig. 5: Filament and asymmetric pillars: presence of pillars breaks the symmetry of evolution.

Summary

We present a novel way for interaction of physically separated metal geometries on nanoscale: Thermal Crowding, based on the fact that that heat adsorption depends on the mass of laser-irradiated metal.

Simplified models and efficient simulations allow to tackle complex setup involving self-consistent fluid - thermal evolution.

References

[1] Allaire, R., Cummings, L., Kondic, L., J. Fluid Mechanics 915, A133 (2021)

[2] Allaire, R., Cummings, L., Kondic, L., Phys. Rev. Fluids 7, 064001 (2022).

[3] Kondic, L., Gonzales, A., Diez J., Fowlkes J., Rack, P., Annu. Rev. Fluid Mech.52, 23 (2020).