COMSOL CONFERENCE
2019 BANGALORE

Numerical Simulation of Melt Hydrodynamics in Laser Micro-Processing using COMSOL Multiphysics®

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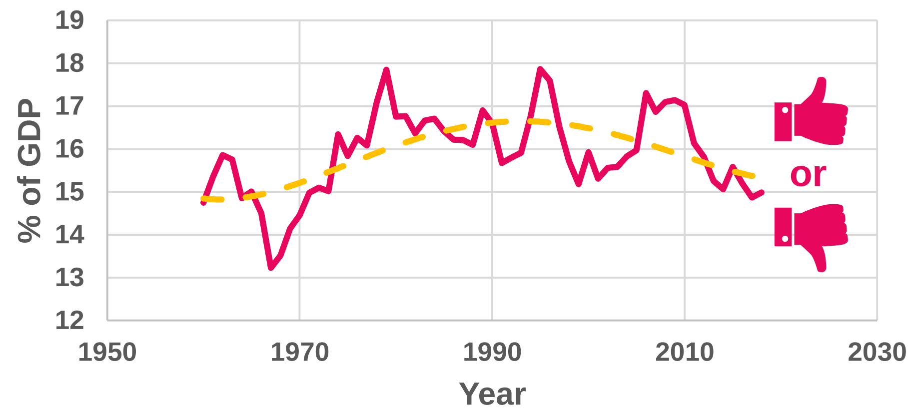
Laser ~~Does~~ Manufacturing Matters~~?~~

- 70% Manufacturing share of global Trade
- 16 % Manufacturing share in Golbal GDP
- $726 Billions Trade surplus of advance economies in innovative goods

Manufacturing, value added (% of GDP, India)



Source: World Bank (OECD National Accounts data files)

laser processing market to grow from USD 6.40 Billion in 2015 to USD 9.75 Billion by 2022, at a CAGR of 6.13% from 2016 to 2022

The laser processing market in APAC is expected to hold the largest share during the forecast period.
India is expected to grow at 19% CAGR to €1 billion by 2020.

- <17 % Manufacturing share in Indian GDP (3rd largest Economy)
- India's share of global manufacturing value added is ~2%
- $138 Billions Trade deficit

Manufacturing is not Monolithic

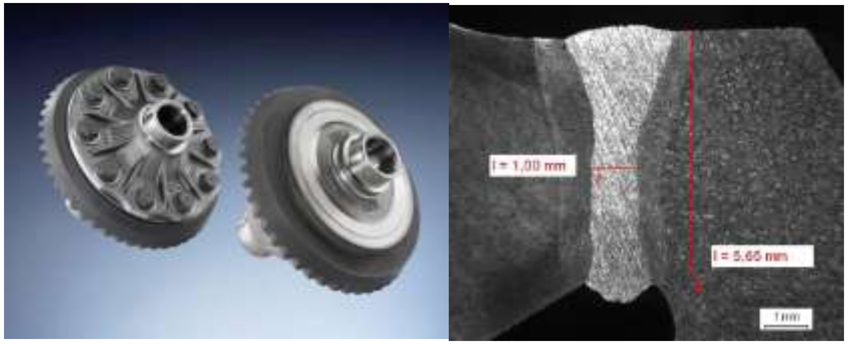
Manufacturing ⟷ Services

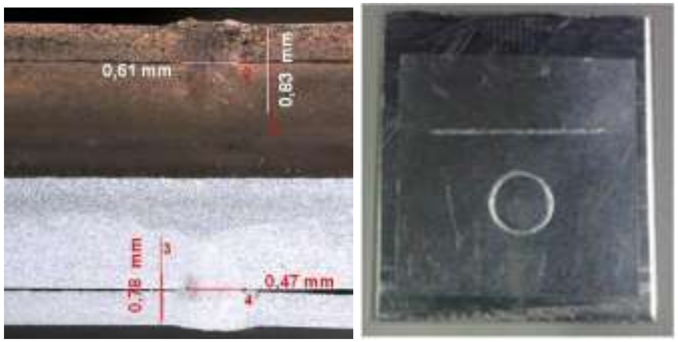
Product Development → Process Development

Target: 25 % Manufacturing share in Indian GDP (Make in India)

MAKE IN INDIA

Pictorial rpresentation of Laser processing Applications in Auto industry



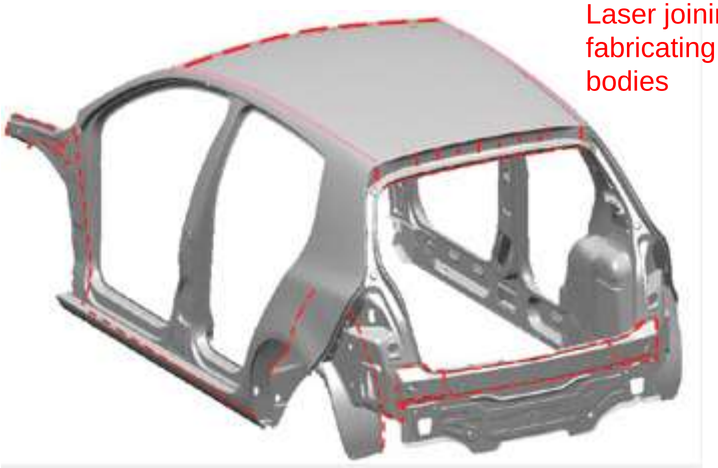


Laser Welding of Bus-bar, Cu-Cu; Al-Al, 3 mm-1 mm

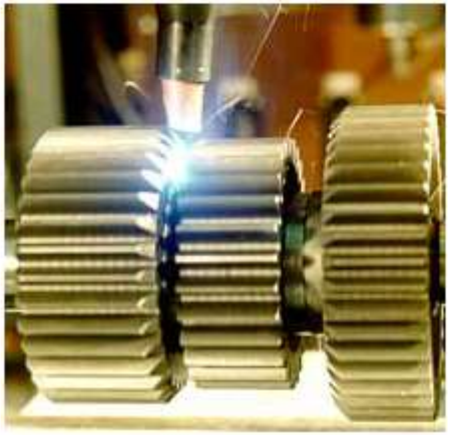
Laser Welding of Differential gears, case hardened steel, Laser power 4kW; image source: https://automotivemanufacturingsolutions.com/wp-content/uploads/2013/12/AMSI_2013_Andrey_Andreev.pdf

Laser Welded Solenoid used in cars

Image source: https://www.twi-global.com/technical-

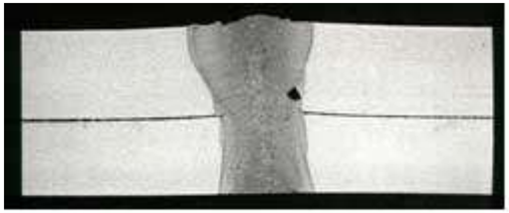


Laser joining for fabricating car bodies

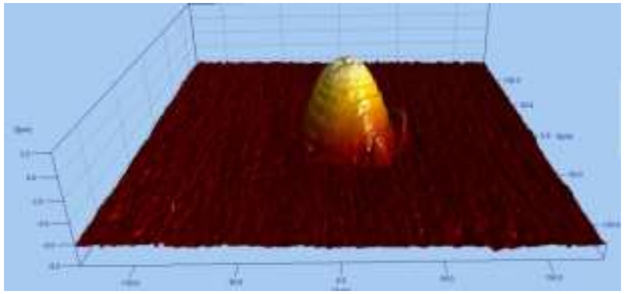


C02 Laser welding of gear component

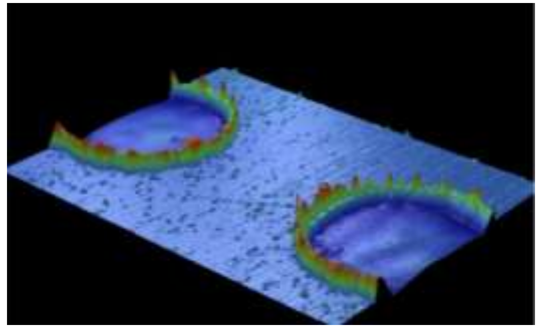
Lap joint in 1.6mm thick 5754 aluminum alloy sheet welded at 5m/min with CO 2 laser



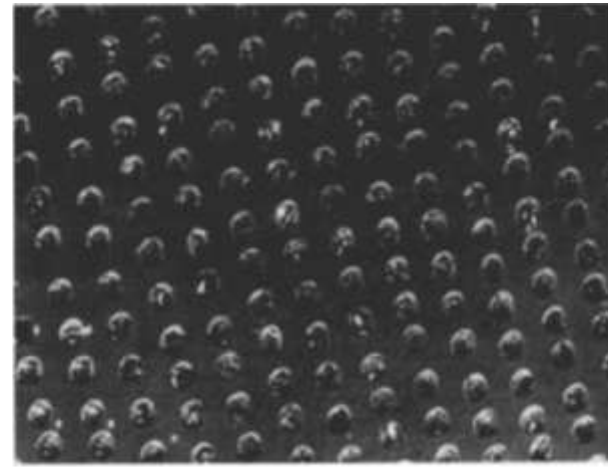
This axle component found on a Mercedes C Class sedan was laser hybrid welded at 177 IPM (4.5 m/min.) with a wire feed rate of 235 IPM (6.0 m/min.) Image source: https://www.thefabricator.com/article/laserwelding/a-look-at-laser-hybrid-welding-in-the-automotive-industry.



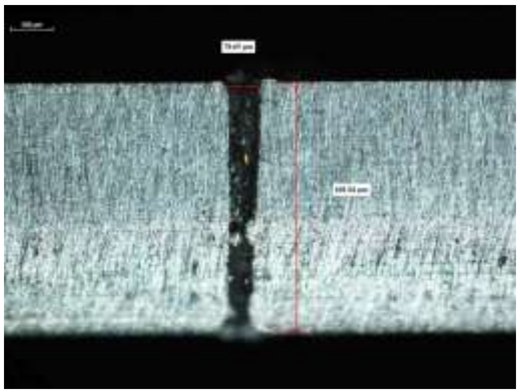
50 µm convex dome in steel



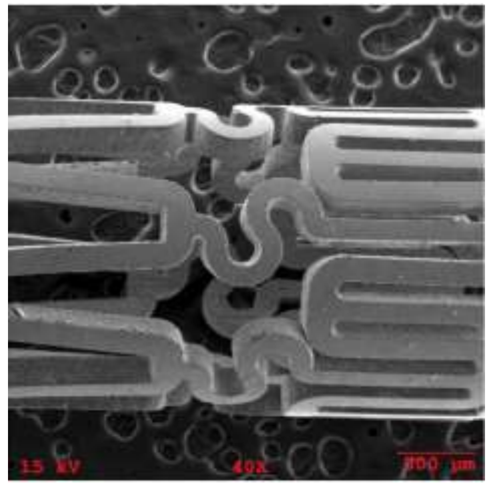
100 µm holes in steel



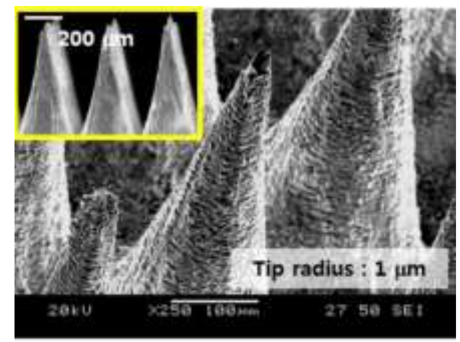
LST regular micro-surface structure in the form of micro-dimples [Etsion et. al.]

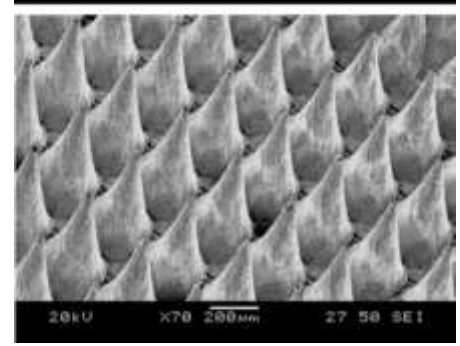


~80 µm hole drilled through a 600 µm Ti sheet

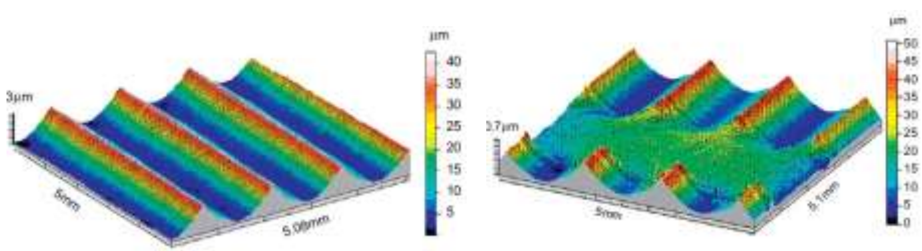


Fiber Laser cut nitinol stent [Baumeister et al.]

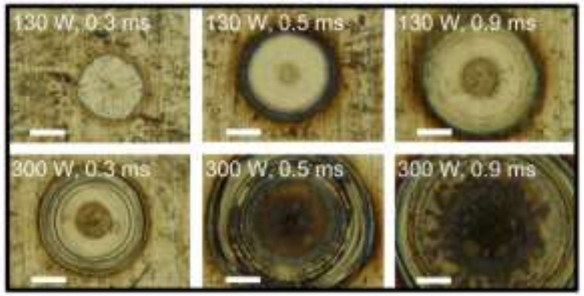




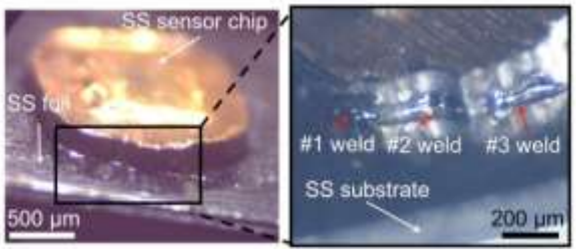
fabricated micro pin array on tungsten [Park et. al.]



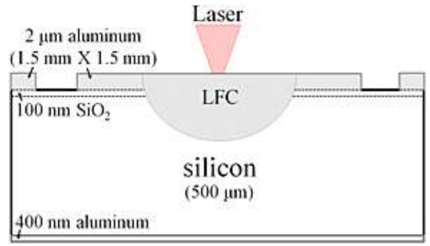
Laser micro polishing



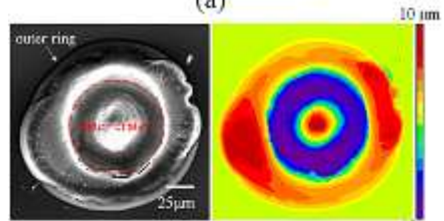
(c)



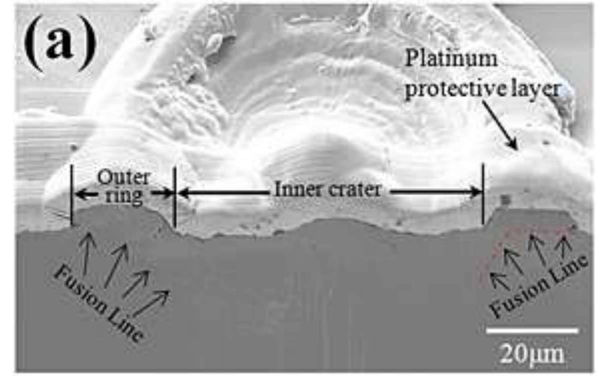
A fabricated sensor welded on SS foil [Chen et. al.]



(a)

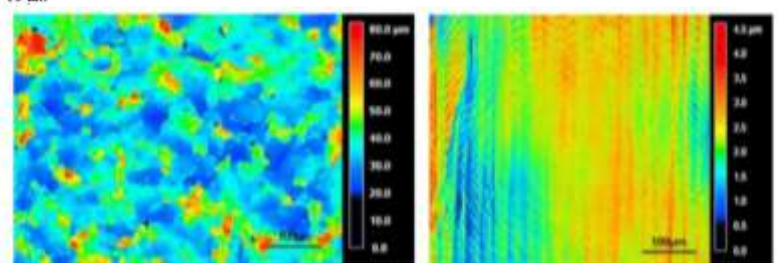


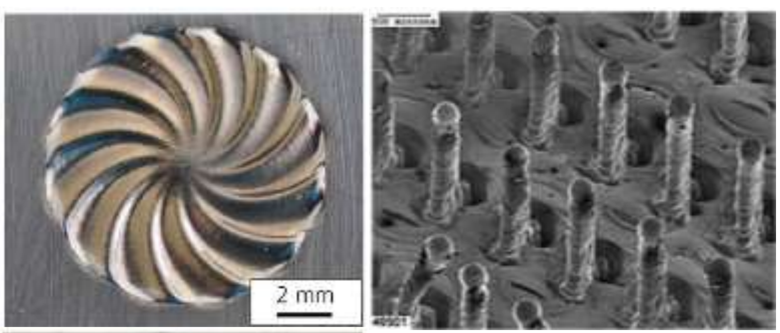
(b)



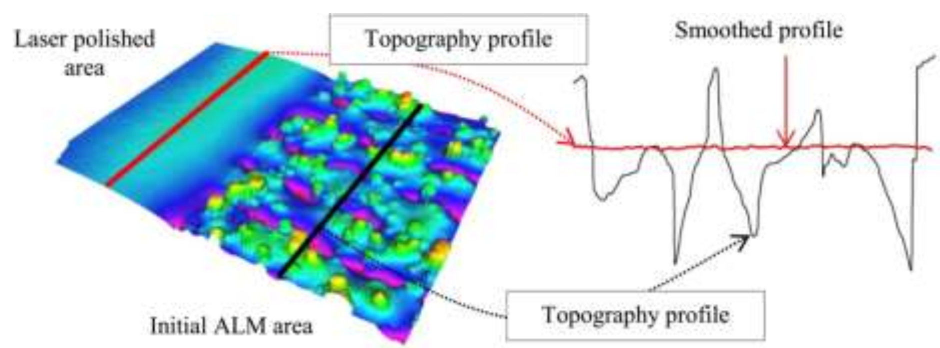
laser-fired contact processed with 260 W laser power, 30 μs pulse length and 70 μm dia. [Raghavan et. al.]

Laser polishing of additive manufactured Ti alloys.
[C. Ma et. al.]





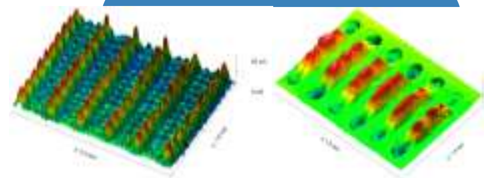
Laser sculpting by re-melting.[Temmler M. Et. al.]



[Benoit Rosa et. al.]

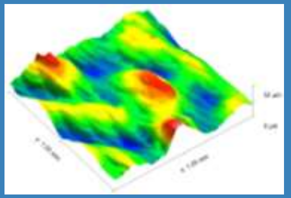
Research Spectrum of Laser micro-sacle Processing of metals

Laser Processing Applications



Large area surface structuring of SS 304 substrate using melt hydrodynamics

~80 μm hole drilled through a 600 μm Ti sheet



Surface asperities homogenization after single laser raster scanning on SS 304

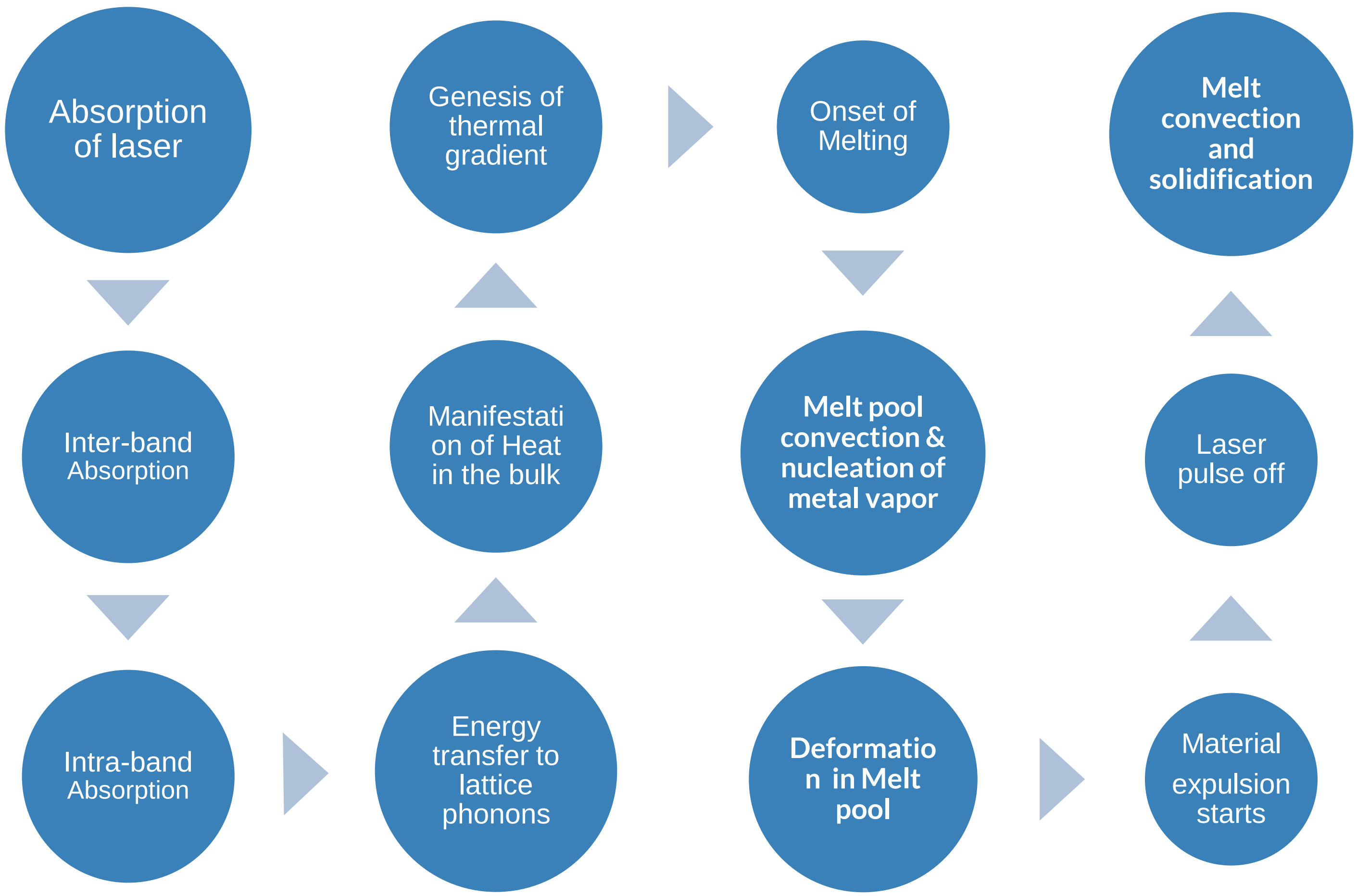
Optical Micrograph of keyhole mode and conduction mode laser μ-welding of SS 304

Limitations of Laser Material processing

- Melt shadowing effect in Laser-drilling.
- Melt-induced recast layer and surface roughness in laser drilling.
- Humping phenomenon in micro laser welding, for micro joining.
- Porosity, Waviness and melt ripples in welded structure.
- Surface over melting in micro polishing and structuring of metals.

Understanding Melt Pool Convection: Water waves analogy

Laser-matter interaction



Key parameters

1

Laser intensity

The order of intensity dictates the mechanism of interaction.

Low intensity- melting.
High intensity- melting and vaporization.

2

Pulse duration

Influences the thermal penetration which in turn affects melt depth, heat affected zone area.

3

Thermo-capillary forces

With the genesis of thermal gradients, marangoni force starts to act on melt surface, producing perturbation over a thin melt layer.

4

Evaporative Heat flux

With vaporization, cooling of subsequent melted surface resulting in temperature dependent melt dynamics.

5

Recoil Pressure

Normal pressure by receeding vapor on melt surface, responisble of melt layer deformation.

6

Surface Tension

Another normal force which balances recoil pressure during heating and responsible for retraction of melt during cooling.

Numerical Simulation

Laser Absorption

• Multiple reflections of laser beam is ignored.
• Fresnel Absorption implemented, where θ_i is angle of incidence which depends upon surface curvature.

$$A_p = 1 - \frac{(n^2 + k^2)cos^2(\theta_i) - 2ncos(\theta_i) + 1}{(n^2 + k^2)cos^2(\theta_i) + 2ncos(\theta_i) + 1}$$

$$A_s = 1 - \frac{(n^2 + k^2)cos^2(\theta_i) - 2ncos(\theta_i) + cos^2(\theta_i)}{(n^2 + k^2)cos^2(\theta_i) + 2ncos(\theta_i) + cos^2(\theta_i)}$$

$$\alpha = \frac{A_p + A_s}{2}$$

Laser Heating

• Heat Transfer module, with temperature dependent thermo-physical properties i.e. ρ(T), κ(T), Cp(T).
• Phase change.
•Radiation loss.
•Ambient heat transfer.
•Evaporative heat loss.

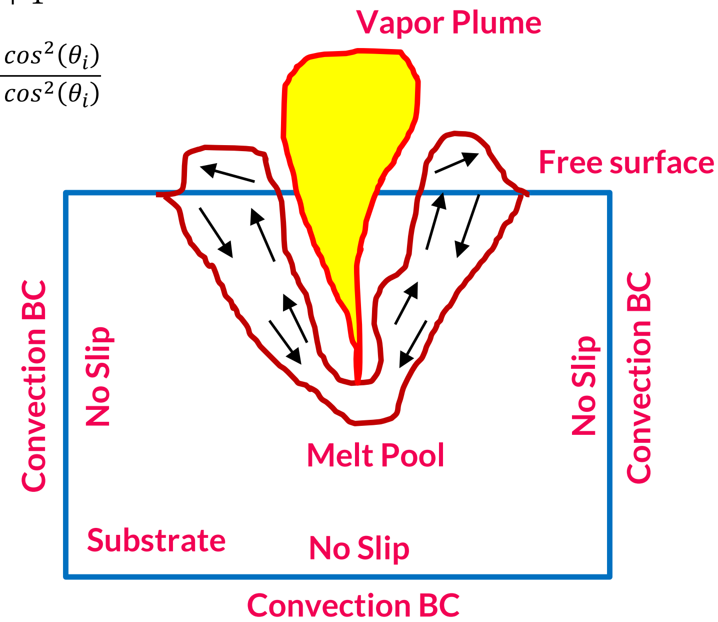
Melt Pool Convection

• Laminar Flow module, with temperature dependent thermo-physical properties i.e. ρ(T), μ(T), σ(T).
•Natural Convection.
•Marangoni Convection (temperature gradient & concentration gradient).
• Vaporization Induced Recoil pressure
• Free Surface (effects of surface tension).

Free Surface Handling : ALE/ Level-Set/ Phase Field

Adapatibility with changing Laser processing operation

Realistic Values of Thermo-physical parameters



Assumptions
•Flow of liquid metal is incompressible Newtonian laminar flow.
•Metallic vapor is regarded as ideal gas and transparent to laser beam.
•Plasma formation and multiple reflections are not taken in account.
•All thermo-physical properties are function of temperature.

Numerical Simulation

Heat transfer + Laminar Flow

Governing Equations

$$\rho C_p^{eq}\left[\frac{\partial T}{\partial t}+\vec{\nabla}\cdot(\vec{u}\,T)\right]=\vec{\nabla}\cdot(k\,\vec{\nabla}T)$$

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+\vec{u}\cdot(\vec{\nabla}\cdot\vec{u})\right)=\vec{\nabla}\cdot\left[-pI+\mu\left(\vec{\nabla}\vec{u}+\left(\vec{\nabla}\cdot\vec{u}\right)^{T}\right)\right]+\rho\vec{g}-\rho_l\beta(T-T_m)\vec{g}$$

$$\vec{\nabla}\cdot\vec{u}=0$$

Boundary Conditions

$$Q_{laser}=2.5\cos(\theta)\,\alpha(\theta)\,f(t)\,\frac{P}{\pi r_o^2}\left[\frac{-((x)-vel*t)^2-(y)^2}{r_o^2}\right]\quad\delta(\emptyset)$$

$$Q_{losses}=-qevap-h[T-T_{amb}]-\varepsilon\sigma[T^4-T_{amb}^4]\;\delta(\emptyset)$$

$$qevap=M_v\times L_v$$

$$M_v=\sqrt{\frac{m}{2\pi k_b T_s}}\times P_{sat}(T_s)\times(1-\beta_r)$$

$$P_{sat}(T_s)=P_{atm}\times exp\left(\frac{M_a L_v}{R}\left(\frac{1}{T_v}-\frac{1}{T_s}\right)\right)$$

$$P_{recoil}=\begin{cases}P_{amb},\;0\le T_s<T_c\\ \frac{1+\beta_r}{2}\times P_{sat}(T_s),\;T_s\ge T_c\end{cases}\qquad\delta(\emptyset)$$

$$\vec{F}=-(P_{recoil}-P_{amb})\vec{n}+\sigma(\vec{\nabla}_s\cdot\vec{n})\vec{n}-\vec{\nabla}_s\sigma$$

Mathematics Module : Moving Interface

ALE

$$\boxed{\frac{\partial\vec{X}}{\partial t}\cdot\vec{n}=\vec{u}}$$

$$n_i\cdot((P_1-P_2)I-\mu_1(\nabla u_1-(\nabla u_1)^T)+\mu_2(\nabla u_2-(\nabla u_2)^T))=\sigma(\nabla_s\cdot n_i)n_i-\nabla_s\sigma$$

$\mu_1>>\mu_2$, pressure jump at interface $P_2-P_1=P_{recoil}$

$$n_i\cdot(\mu(\nabla u-(\nabla u)^T)=-P_{recoil}n_i+\sigma(\nabla_s\cdot n_i)n_i-\nabla_s\sigma$$

$$\sigma=\sigma_m-\gamma_{pm}(T-T_m)-R_g T\,\Gamma_s\ln(1+k_1 a_i e^{-\frac{\Delta H_o}{R_g T}})$$

$$\frac{d\sigma}{dT}=-\gamma_{pm}-R_g T\,\Gamma_s\ln(1+Ka_i)-\frac{Ka_i}{1+Ka_i}\frac{\Gamma_s\Delta H_o}{T}$$

Mesh Smoothening Type
- Hyperelastic
- Yeoh
- Mesh size must be comparable to deformation at each time step

Fully coupled solver

Level-set

$$\frac{\partial\emptyset}{\partial t}+\vec{u}\cdot\vec{\nabla}\emptyset+\gamma\vec{\nabla}\cdot\left[\emptyset(1-\emptyset)\frac{\vec{\nabla}\emptyset}{|\vec{\nabla}\emptyset|}-\varepsilon\vec{\nabla}\emptyset\right]=0$$

$$S_{cont}=\delta(\emptyset)\,M_v\left(\frac{\rho_l-\rho}{\rho^2}\right)$$

$$S_{ls}=\delta(\emptyset)\,M_v\left(\frac{\emptyset}{\rho_l}+\frac{1-\emptyset}{\rho_v}\right)$$

Alternative to ALE
- Extreme Topological Changes
- Suitable for melt expulsion regime
- Interface aberration occurs during vaporization dominant regime with realistic values of surface tension

Phase-field

$$\frac{\partial\phi}{\partial t}+u\cdot\nabla\phi=\nabla\cdot\frac{\gamma\lambda}{\varepsilon^2}\nabla\psi$$

$$\psi=-\nabla\cdot\varepsilon^2\nabla\phi+(\phi^2-1)\phi$$

$$\delta=6|\phi(1-\phi)||\nabla\phi|$$

$$\nabla\cdot\vec{u}=\delta*(M_v*(\frac{\rho_l-\rho}{\rho^2}))$$

$$\frac{\partial\phi}{\partial t}+u\cdot\nabla\phi-\delta*(M_v*(\frac{\rho_l-\rho}{\rho^2}))=\nabla\cdot\frac{\gamma\lambda}{\varepsilon^2}\nabla\psi$$

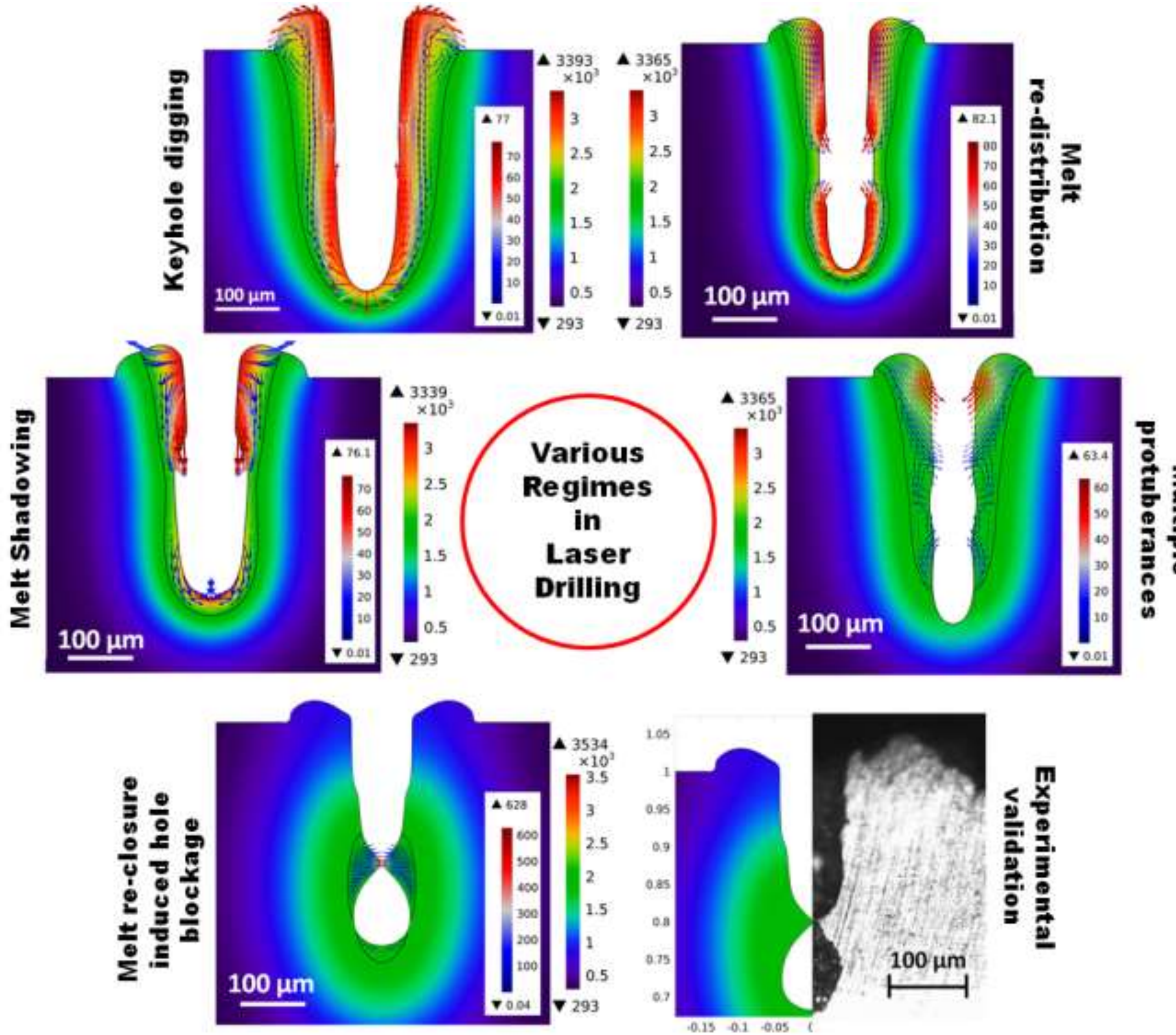
Alternative to ALE
- Extreme Topological Changes
- Suitable for vaporization dominant regime with realistic values of surface tension

Meshing
- Interface thickness
- Mesh size must resolve moving interface

Segregated solver $\delta(\emptyset)\rightarrow T\rightarrow U$

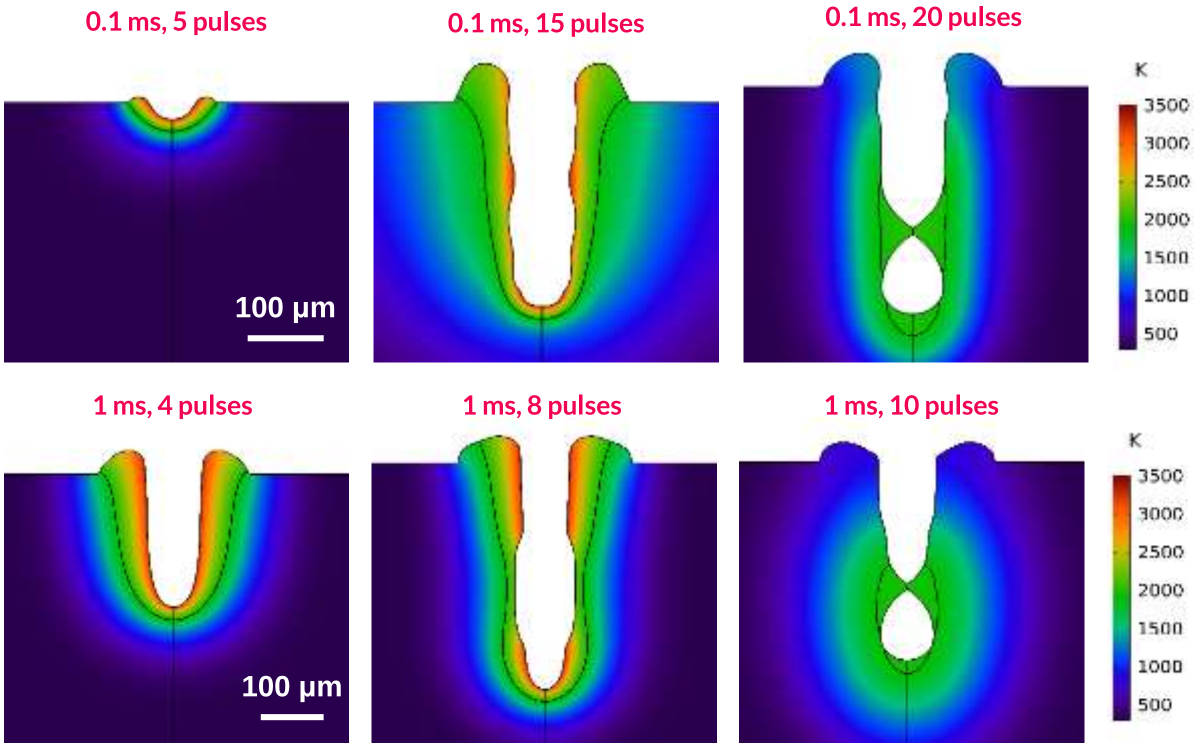
Numerical Simulation of Melt Hydrodynamics in Laser drilling

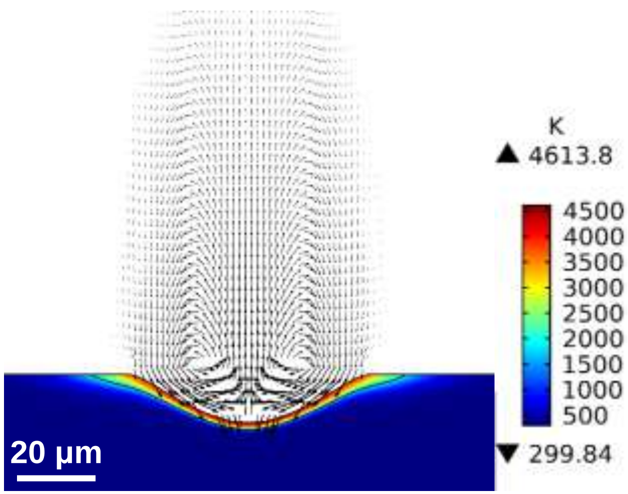
Laser power 200W
Pulse width 1 ms
Rep rate 10Hz
Material: Ti
Radius:- 100 μm



Numerical Simulation of Melt Hydrodynamics in Laser drilling

Role of Pulse Width

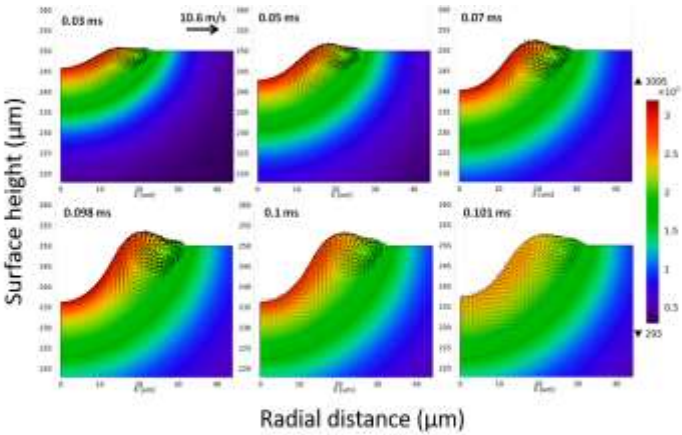


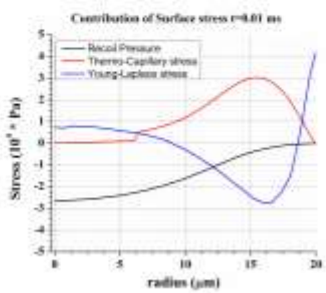


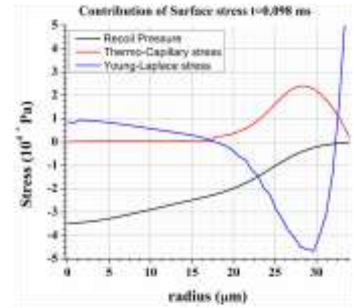
Transient melt pool dynamics in laser drilling, Fluence = 3J/cm2, at 20 ns irradiation time.

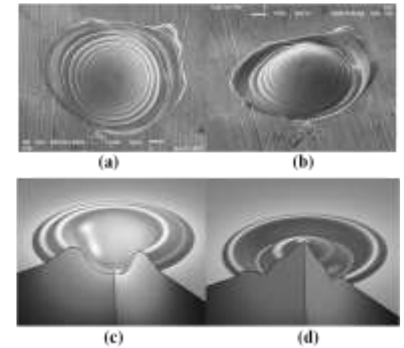
Laser Surface texturing: Micro hump conundrum

Transient Melt Pool Hydrodynamics

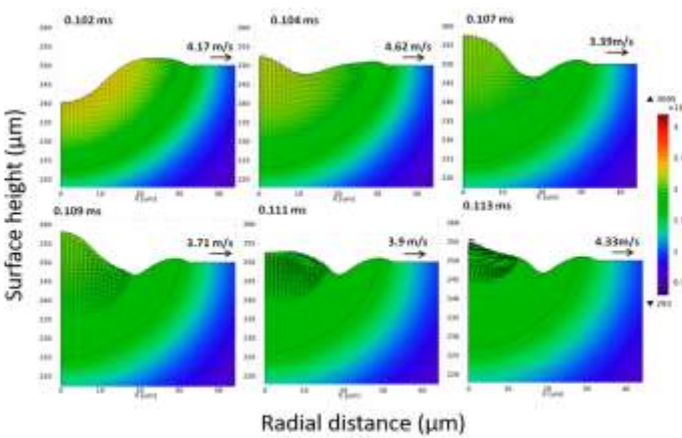


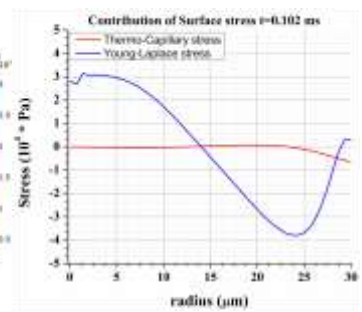


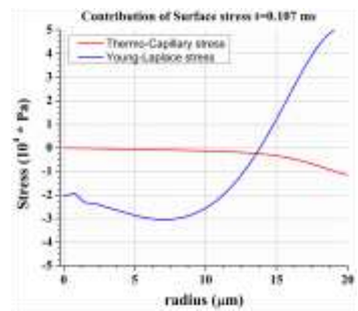


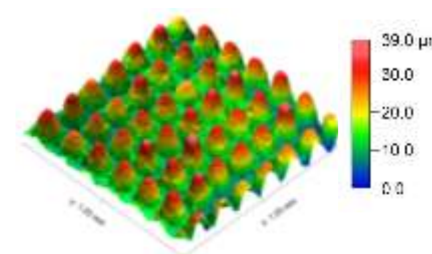


Qualitative comparison of surface topography for P=70W, dia=73µm. (a) SEM micrograph (top view) (b) SEM micro graph (tilted view) (c) 270º revolute profile of simulated melt geometry at t=0.1 ms (d) t=0.4 ms.

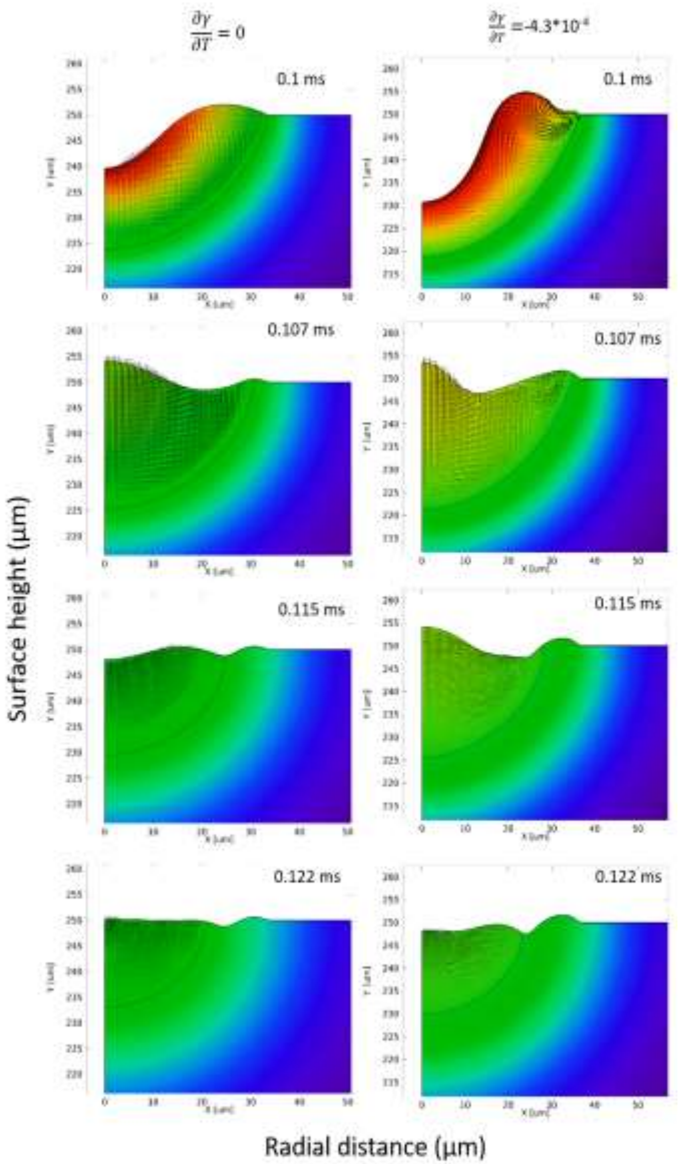


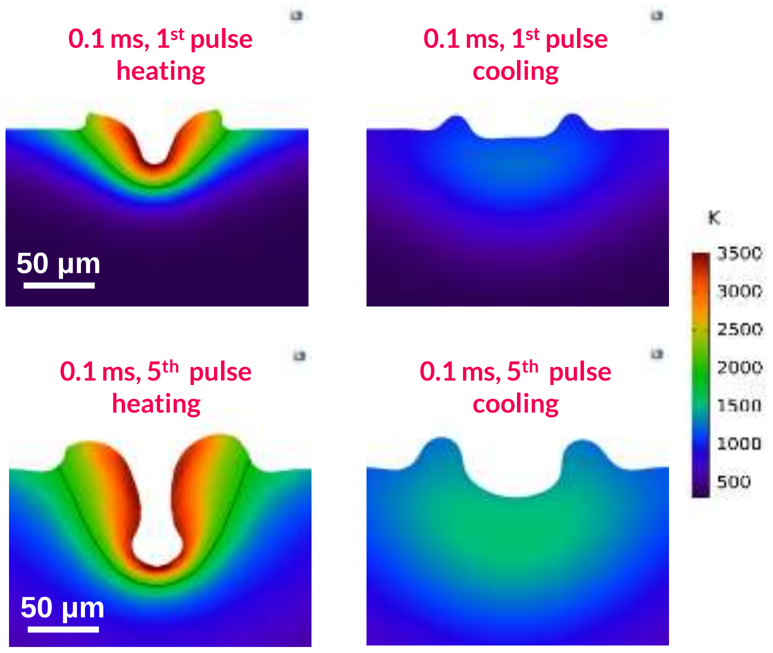






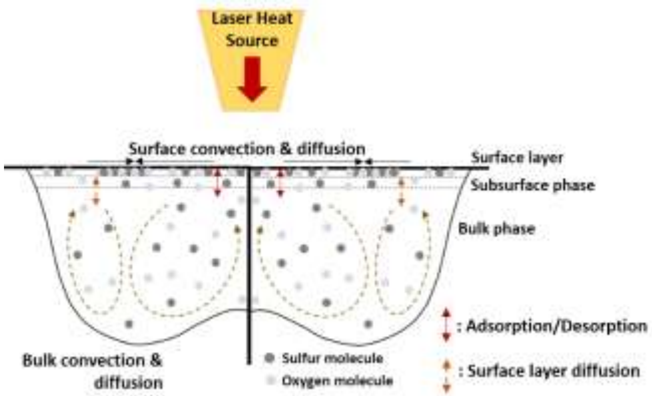
Laser Surface texturing: Bump to crater transition

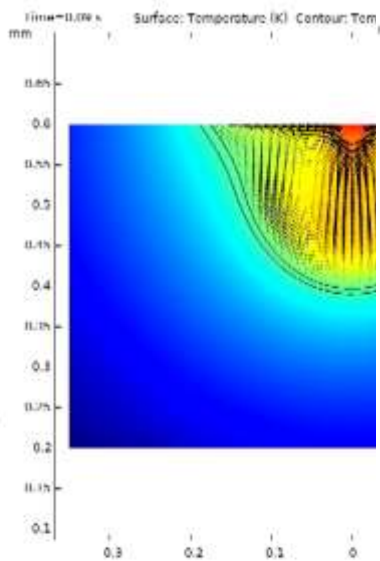


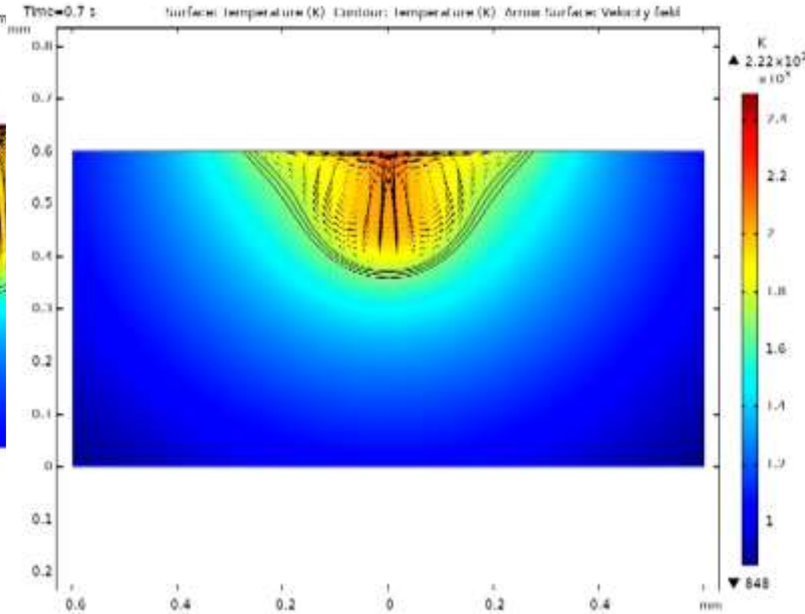


P= 100W, 0.1 ms, Ti6AlV4 , $\frac{\partial\gamma}{\partial T} = -2.8 \times 10^{-4}$ N/(m*K)

Melt Hydrodynamics in Conduction mode Laser welding







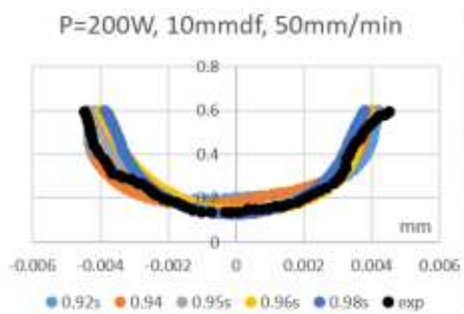
$$\frac{\partial C_i}{\partial t} + (\vec{u} \cdot \nabla) C_i = D_i \nabla^2 C_i$$

$$\frac{\partial \Gamma_i}{\partial t} + \nabla_s (\Gamma_i \vec{u_s}) = \nabla_s^2 \Gamma_i + S_i$$

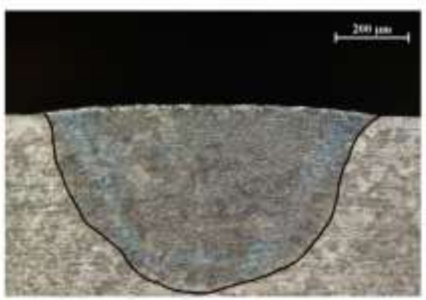
$$S_i = \beta_i' C_{s,i} \left(\Gamma_{\infty,i} - \Gamma_i - \sum_j \Gamma_j \frac{\Gamma_{\infty,i}}{\Gamma_{\infty,j}} \right) - \alpha_i' \Gamma_i, \qquad j \geq 2.$$

$$C_i = \frac{\alpha_i'}{\beta_i'} \left(\frac{\Gamma_i}{\Gamma_{\infty,i} - \Gamma_i - \sum_j \Gamma_j \frac{\Gamma_{\infty,i}}{\Gamma_{\infty,j}}} \right) \qquad a_{i,var,cor}' = C_i p_i' f_i$$

$$\left(\frac{\partial \sigma}{\partial T} \right)_{multi} = \sum_i -A_{\sigma,i} - RT\, ln\left(1 + K_{seg,i}' a_i'\right) - \frac{K_{seg,i}' a_i'}{1 + K_{seg,i}' a_i'} \frac{\Gamma_{\infty,i}' \Delta H_i^o}{T}$$



(a)



(b)

Melt Hydrodynamics in Keyhole mode Laser micro welding

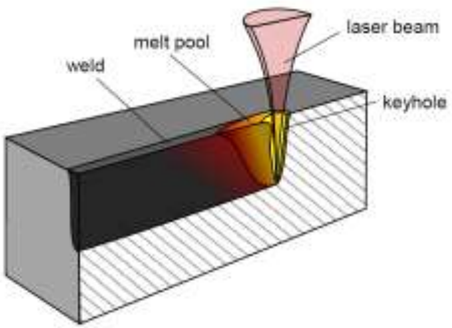
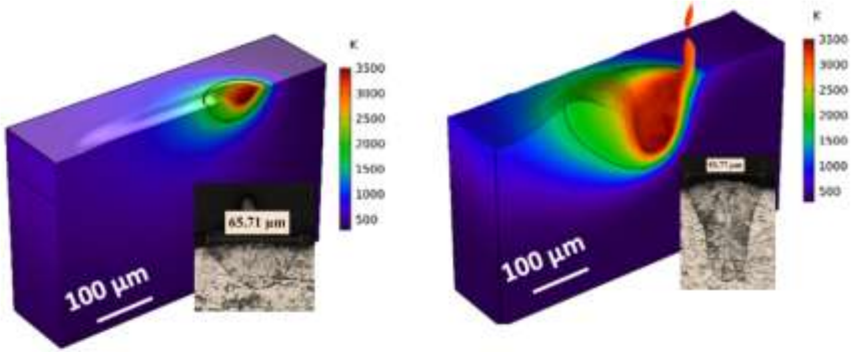
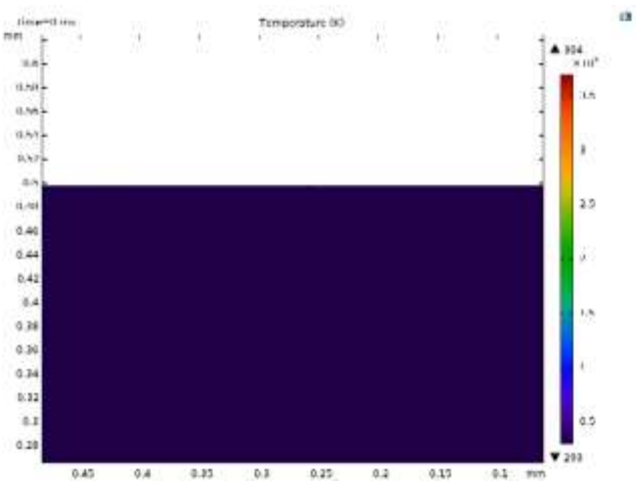
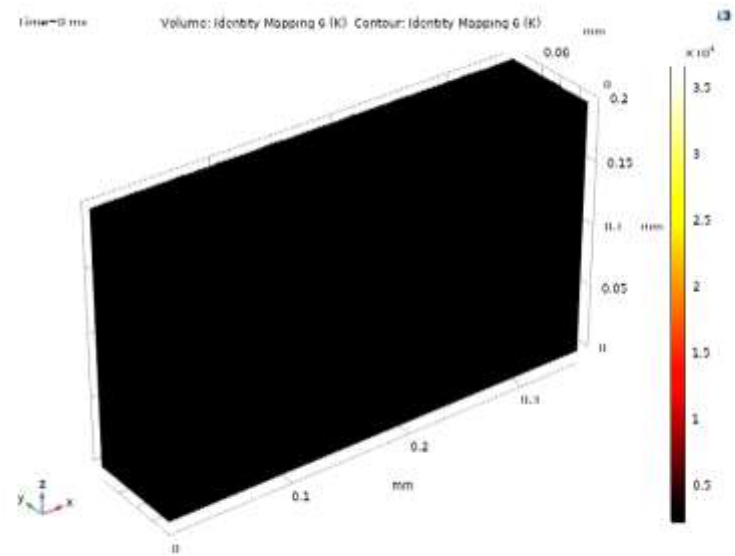


Image Source: http://www.ionix.fi/content/wp-content/uploads/2015/10/laser_welding.jpg

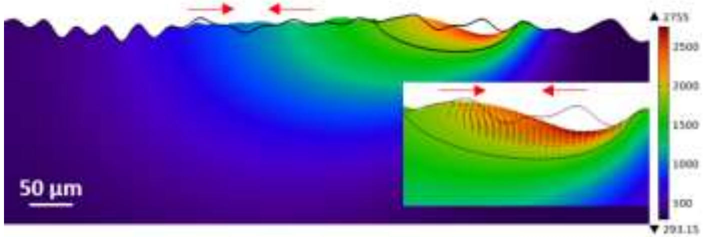


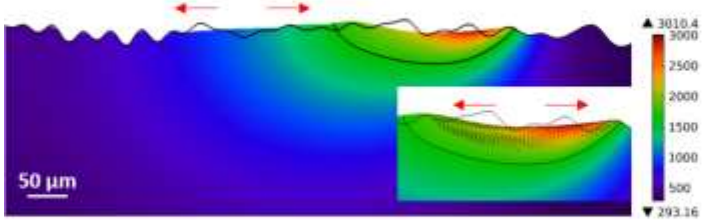
(a) (b)

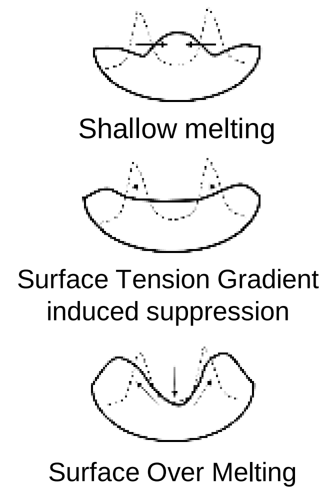


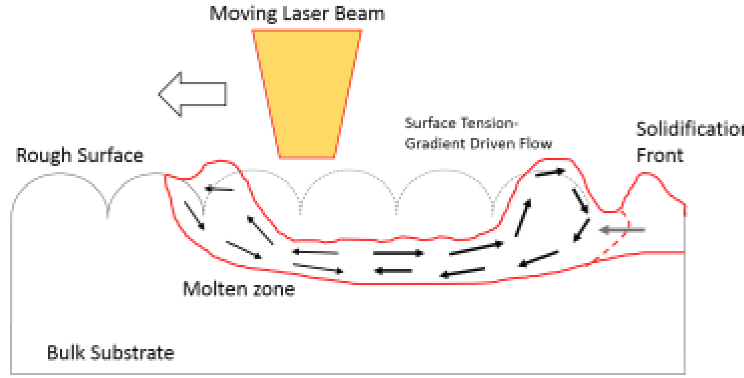


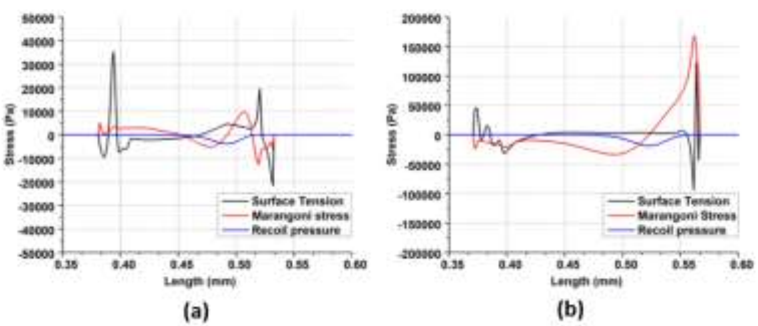
Melt Hydrodynamics in Laser polishing

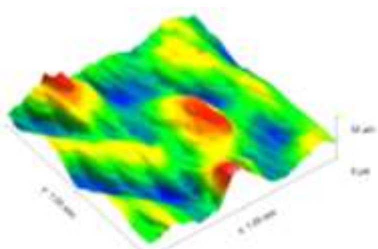


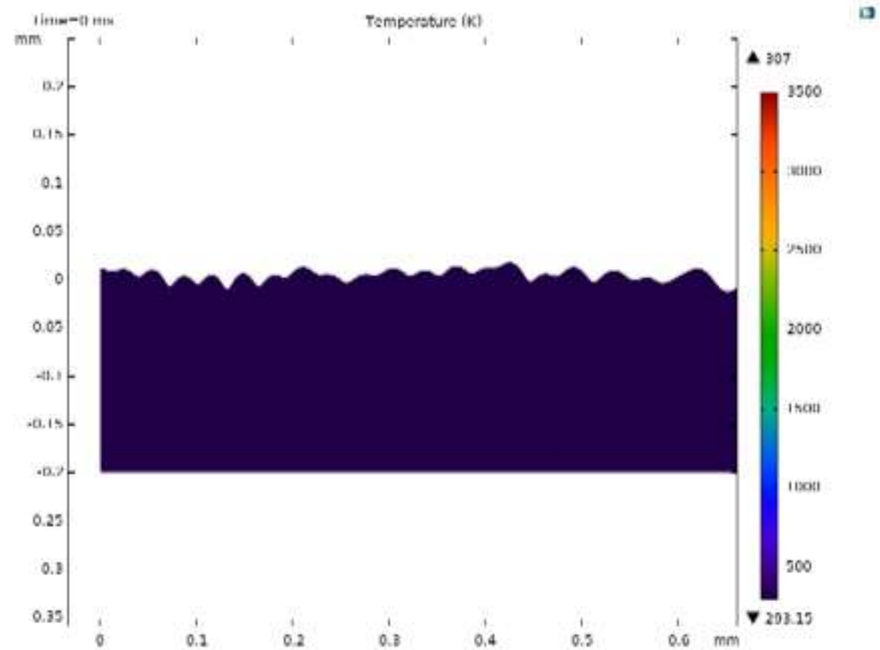












Thanks!

Any questions?

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