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Resource-efficient welding processes through numerical simulation and optimization

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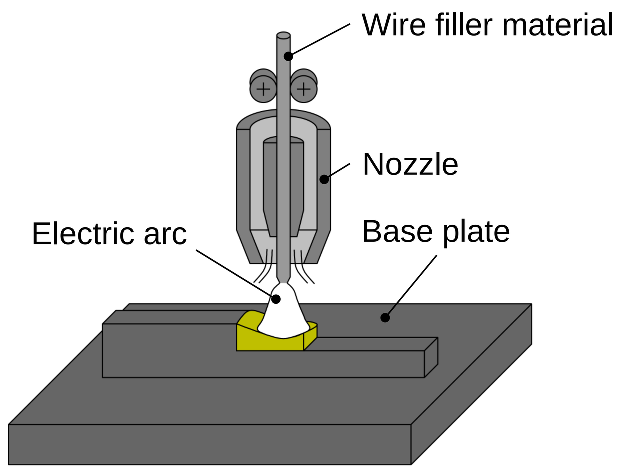
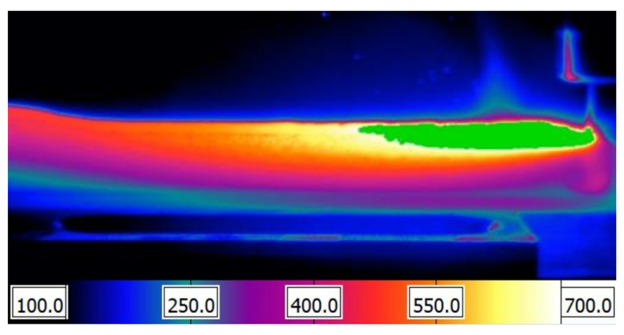
Scope

- Wire arc additive manufacturing
  - High deposition rates
  - Small cooling rates
  - High energy input
  - Multi-material design



- Cooling times required to prevent overheating of the structure
  - Usually chosen based on experience
  - ⟶ Lack of reproducibility
  - ⟶ Unwanted part properties
  - ⟶ Extended process time



⟶ Provide a numerical tool for process parameter optimization
- ⟶ Cooling time
- ⟶ Welding velocity

Optimization Problem

Initial boundary value problem

Transient heat conduction equation

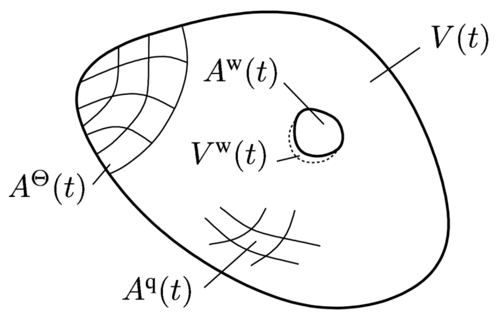
$$\rho(\vec{x})c_p(\Theta)\dot{\Theta}(\vec{x},t) = -\operatorname{div}\vec{q}(\vec{x},t) + r_\Theta(\vec{x},t)$$

Constitutive equation (Fourier's model)

$$\vec{q}(\vec{x},t) = -\kappa(\Theta)\operatorname{grad}\Theta(\vec{x},t)$$

Boundary and initial conditions

$$\Theta(\vec{x},t) = \overline{\Theta}(\vec{x},t) \quad \text{on } A^\Theta(t)$$
$$\vec{q}(\vec{x},t)\cdot\vec{n}(\vec{x}) = \hat{q}(\vec{x},t) \quad \text{on } A^w(t)$$
$$\vec{q}(\vec{x},t)\cdot\vec{n}(\vec{x}) = \overline{q}(\Theta(\vec{x},t)) \quad \text{on } A^q(t)$$
$$\Theta(\vec{x},t_0) = \Theta_0(\vec{x}) \quad \text{at } t_0$$



Convection and non-linear radiation

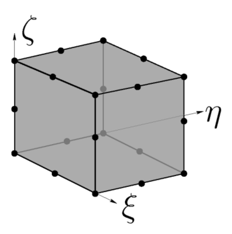
$$\overline{q}(\Theta) = h(\Theta)\,(\Theta-\Theta_\infty) + \sigma\epsilon(\Theta)\,(\Theta^4-\Theta_\infty^4)$$

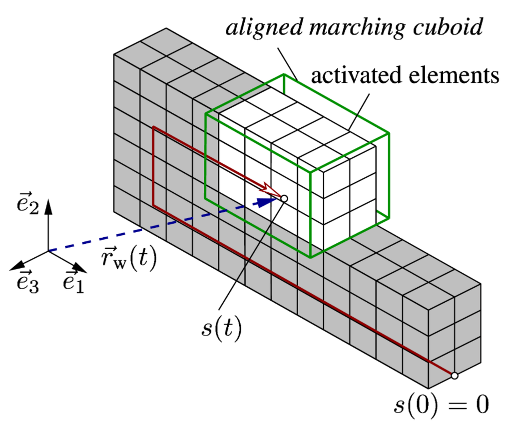
⟶ Geometry evolves during the process

Discretization

Spatial discretization with finite elements

$$\longrightarrow \quad \boldsymbol{g}\left(t_{n+1}, \boldsymbol{\Theta}_{n+1}, \frac{\boldsymbol{\Theta}_{n+1}-\boldsymbol{\Theta}_n}{\Delta t_n}\right) = \boldsymbol{0}$$





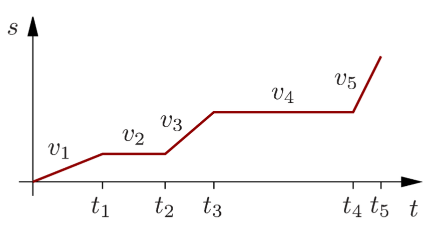
Temporal discretization with Backward Euler method

⟶ Inactive element method (element activation ⟶ non-smooth model response)

Optimization

Goal: Minimize process time

$$\min_{\boldsymbol{\kappa}} T(\boldsymbol{\kappa}) \quad \text{i.e.} \quad \boldsymbol{\kappa}^* = \arg\min_{\boldsymbol{\kappa}} T(\boldsymbol{\kappa})$$



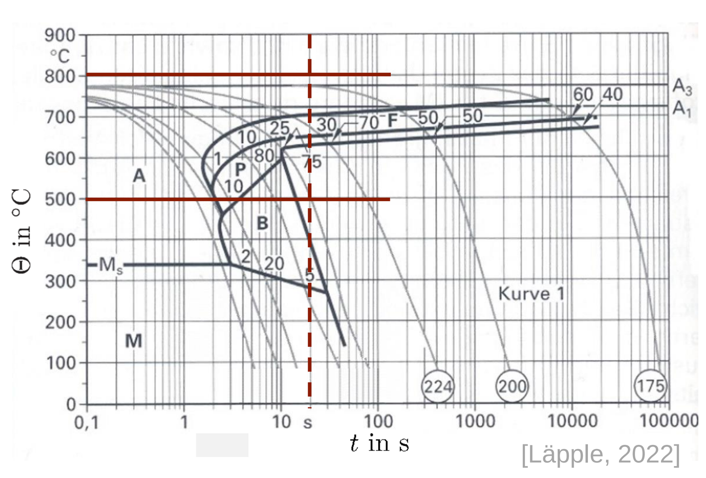
Process related inequality constraints

I. Welding velocity
$v_w(t) \geq v_{w,min}, \quad v_w(t) \leq v_{w,max}$

II. Cooling time (process)
$\Delta t_c \geq 0$

III. Cooling time (structure)
$\Delta t_{8/5} \leq \Delta t_{8/5,max}$

IV. Interlayer temperature
$\Theta_{int} \leq \Theta_{int,max}$



⟶ Gradient-free optimization using Nelder-Mead Simplex algorithm

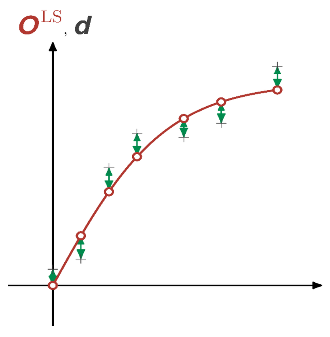
Reference: Tröger, J.-A., Hartmann, S., Treutler, K., Potschka, A., Wesling, V.: *Simulation-based process parameter optimization for wire arc additive manufacturing.* Submitted to Progress in Additive Manufacturing

Model Calibration

Model calibration using non-linear least-squares method

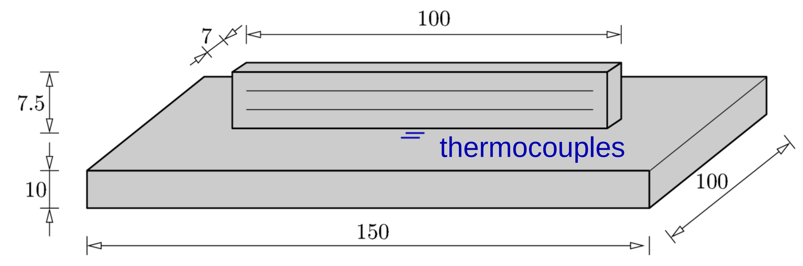
$$f(\boldsymbol{\beta}) = \frac{1}{2}\|\boldsymbol{r}(\boldsymbol{\beta})\|^2 \qquad \min_{\boldsymbol{\beta}} f(\boldsymbol{\beta}) \quad \text{i.e.} \quad \boldsymbol{\beta}^* = \arg\min_{\boldsymbol{\beta}} f(\boldsymbol{\beta})$$

- Residuum: $\boldsymbol{r}(\boldsymbol{\beta}) = \boldsymbol{O}^{LS}(\boldsymbol{S}^{LS}(\boldsymbol{\beta})) - \boldsymbol{d}$
- Experimental data: $\boldsymbol{d}$
- Model response: $\boldsymbol{O}^{LS}(\boldsymbol{S}^{LS}(\boldsymbol{\beta}))$ → Finite element simulation
- Parameters: $\boldsymbol{\beta} = \{c_1, c_2, c_3\}^T$



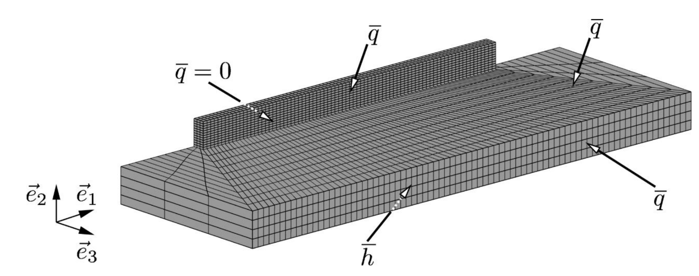
Experimental setup – three-layered vertical wall

arc voltage	arc current	wire feed rate	welding velocity
17.7 V	147.7 A	4 m/min	50 cm/min



Numerical model

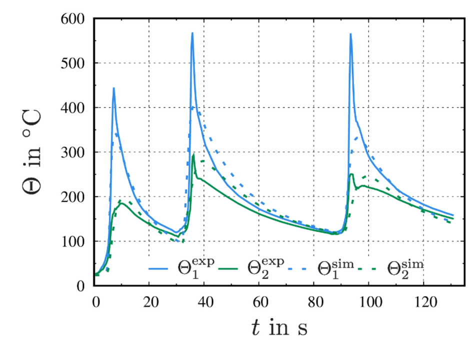
- Symmetry in $\vec{e}_3$-direction
- Goldak's double ellipsoidal heat source
- Ansatz for convection on free surfaces
$h(\Theta) = c_1 \tanh(c_2\Theta) + c_3$

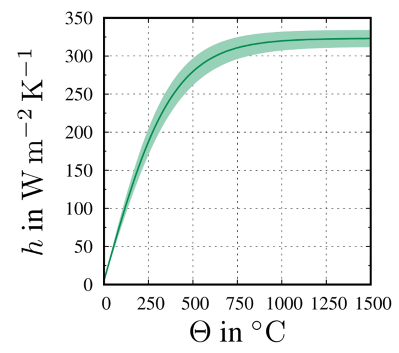


Calibration result and uncertainty quantification

→ 77 finite element simulations required during calibration

parameter	value ± uncert.	dimension
c_1	318 ± 11	$\mathrm{W\,m^{-2}\,K^{-1}}$
c_2	$2.6\times10^{-3} \pm 2\times10^{-4}$	°C
c_3	5.2 ± 0.6	$\mathrm{W\,m^{-2}\,K^{-1}}$





Results

Penalty objective function for process parameter optimization

$$\hat{f}(\boldsymbol{\kappa}) = w_t \sum_{i=1}^{n_l} \underbrace{\left(\Delta t_w^{(i)} + \Delta t_c^{(i)}\right)}_{\text{welding and cooling time per layer}} + \underbrace{p\,\langle \Delta t_{w,min} - \Delta t_w^{(i)}\rangle}_{\text{constraint max. welding velocity}} + \underbrace{p\,\langle \Delta t_w^{(i)} - \Delta t_{w,max}\rangle}_{\text{constraint min. welding velocity}} + \underbrace{p\,\langle -\Delta t_c^{(i)}\rangle}_{\text{constraint positive cooling time}}$$
$$+ \underbrace{p\,\langle O_{8/5}^{(i)}(\boldsymbol{S}(\boldsymbol{\kappa})) - \Delta t_{8/5,max}\rangle}_{\text{constraint layer cooling}}\Big) + \underbrace{w_\Theta\, p \sum_{j=1}^{n_l-1} \langle O_{int}^{(j)}(\boldsymbol{S}(\boldsymbol{\kappa})) - \Theta_{int,max}\rangle}_{\text{constraint interlayer temperature}} \qquad \langle x\rangle = \begin{cases} 0 & \text{if } x<0,\\ x & \text{if } x\geq 0\end{cases}$$

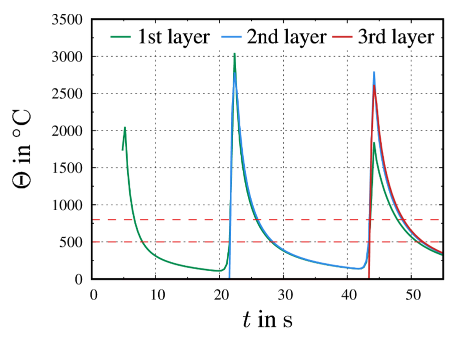
- Parameters: $\boldsymbol{\kappa} = \{\Delta t_w^{(i)}, \Delta t_c^{(i)}\}^T$
- Weighting factors: $w_t = \mathrm{s}^{-1}$, $w_\Theta = {}^\circ\mathrm{C}^{-1}$
- Penalty factor: p

$v_{w,min}$	$v_{w,max}$	$\Delta t_{8/5,max}$	$\Theta_{int,max}$
$5\,\mathrm{mm\,s^{-1}}$	$10\,\mathrm{mm\,s^{-1}}$	20 s	180 °C

Process parameter optimization – three-layered vertical wall

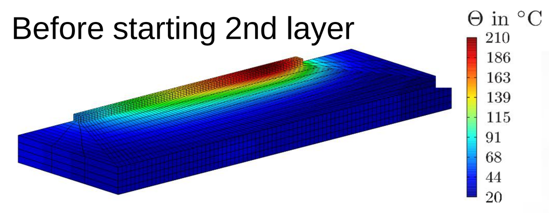
- Optimized parameters: $\Delta t_w^{(1)} = 10\,\mathrm{s}$, $\Delta t_w^{(2)} = 14.4\,\mathrm{s}$, $\Delta t_w^{(3)} = 13.2\,\mathrm{s}$, $\Delta t_c^{(1)} = 5.1\,\mathrm{s}$, $\Delta t_c^{(2)} = 7.9\,\mathrm{s}$
- Welding velocities: $v_w^{(1)} = 10\,\mathrm{mm\,s^{-1}}$, $v_w^{(2)} = 6.95\,\mathrm{mm\,s^{-1}}$, $v_w^{(3)} = 7.56\,\mathrm{mm\,s^{-1}}$
- Cooling time: $\Delta t_{8/5}^{(i)} \approx 3\,\mathrm{s}$, $i = 1,2,3$
- Interlayer temperature: $\Theta_{int}^{(1)} = 174\,^\circ\mathrm{C}$, $\Theta_{int}^{(2)} = 180\,^\circ\mathrm{C}$

→ 124 finite element simulations required

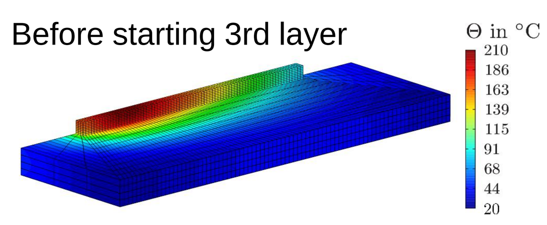


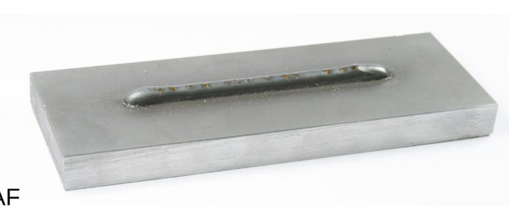
Cooling behavior

Before starting 2nd layer



Before starting 3rd layer





Structure manufactured with optimized parameters

⟶ Optimized parameters satisfy process- and material-related constraints

⟶ Process time reduced by 48% compared to manually chosen parameters

Outlook

- Extension to variable arc voltage and arc current within optimization
  ⟶ Control energy input during process
- Further development of modelling capabilities
  - Heat source model
  - Complex welding paths