The PyRolL Integral Thermal Plugin

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Model approach

The following is taken from [[1]].

The thermal model implemented here is a simple approach estimating the temperature changes during a whole roll pass or transport, without local resolution. Roll passes and transports differ in the main contributions to temperature change and the geometry of the workpiece.

Transports

The cross-section of the workpiece can be assumed as constant over the whole length of the transport. The main contributions to temperature change are here due to convection ΔT_K and to radiation ΔT_R. Additionally one may apply some water cooling in the transport, e.g. for modelling a cooling range.

$$\Delta T = \Delta T_\mathrm{K} + \Delta T_\mathrm{W} + \Delta T_\mathrm{R}$$

Convection Convection heat transfer is modelled using a simple heat transfer coefficient model as shown below. α_K is hereby the transfer coefficient α_K, T_∞ the environment temperature, t the time, u_P the circumference of the profile cross-section, A_P the cross-section area, ρ the density and c_p the heat capacity. For α_K a value around $15\,\frac{\mathrm{W}}{\mathrm{m^2K}}$ can be assumed.

$$\Delta T_\mathrm{K} = \frac{\alpha_\mathrm{K} u_\mathrm{P} \left(T - T_\infty\right) t}{\rho c_\mathrm{p} A_\mathrm{P}}$$

Water cooling The approach for water cooling is generally equivalent to convection. It is also modelled using a transfer coefficient model, but here with the temperature of the water T_W instead of T_∞. Typical values of the transfer coefficient α_W reside around $150\,\frac{\mathrm{W}}{\mathrm{m^2K}}$.

[1] A. Hensel, P. I. Poluchin, W. P. Poluchin: Technologie der Metallformung. Deutscher Verlag für Grundstoffindustrie, Leipzig, 1990

$$\Delta T_{\mathrm{W}} = \frac{\alpha_{\mathrm{W}} u_{\mathrm{P}} \left(T - T_{\mathrm{W}}\right) t}{\rho c_{\mathrm{p}} A_{\mathrm{P}}}$$

Radiation Radiation is modelled using the Stefan Boltzmann approach of the grey radiator. σ_{B} is the Stefan Boltzmann radiation constant, ε_{R} the relative radiation coefficient of the grey radiator in the range between 0 (white radiator) and 1 (black radiator). Values of ε_{R} can be obtained from most volumes of plates. σ_{B} is $5.670374419\ldots \times 10^{-8}\,\frac{\mathrm{W}}{\mathrm{m^2 K^4}}$.

$$\Delta T_{\mathrm{R}} = \frac{\sigma_{\mathrm{B}} \varepsilon_{\mathrm{R}} u_{\mathrm{P}} \left(T^4 - T_{\infty}^4\right) t}{\rho c_{\mathrm{p}} A_{\mathrm{P}}}$$

Roll passes

In roll passes the main contributions to temperature change are due to roll contact ΔT_{C} and due to deformation heat ΔT_{D} as shown below. Convection and radiation at the free surfaces are neglected, since they are comparably small. The geometry in the pass is quite complicated, so it must be approximated.

$$\Delta T = \Delta T_{\mathrm{C}} + \Delta T_{\mathrm{D}}$$

Roll Contact Roll contact heat transfer is modelled accordingly by a heat transfer coefficient model. A_{d} is the contact area between workpiece and roll, V the volume of workpiece within the roll gap and T_{R} the temperature of the rolls. V is hereby approximated by $V = L_{\mathrm{d}} \left(A_{\mathrm{P0}} + A_{\mathrm{P1}}\right)/2$, where the $A_{\mathrm{P}i}$ are the cross-sections of incoming resp. outgoing profile. The value of α_{C} is typically in the range between 2000 and 6000 $\frac{\mathrm{W}}{\mathrm{m^2 K}}$. Influences of cooling water and lubricants can be included within this factor.

$$\Delta T_{\mathrm{C}} = 2 \frac{\alpha_{\mathrm{C}} A_{\mathrm{d}} \left(T - T_{\mathrm{R}}\right) t}{\rho c_{\mathrm{p}} V}$$

Deformation Heat The heat generated by deformation can be estimated using the flow stress k_{f} and the equivalent strain applied in the pass $\Delta\varphi_{\mathrm{V}}$. An efficiency factor of η is included to take energy saved in microstructure into account. $\eta = 1$ means that all forming energy is dissipated as heat, $\eta = 0$, however, that all energy is saved in microstructure. $\eta = 0.95$ is a common value. Instead of k_{f} the deformation resistance k_{W} can be used to include effects of friction and inhomogeneity.

$$\Delta T_{\mathrm{D}} = \eta \frac{k_{\mathrm{f}} \Delta\varphi_{\mathrm{V}}}{\rho c_{\mathrm{p}}}$$

Usage instructions and implementation details

The model specifies and implements several hooks for the terms and values mentioned above. These are explained in the following. Most of them have default implementations, provide your own or set constant attributes on the objects to override their behavior.

For using the plugin you *must* implement the following hooks or set constant attributes:

- `Profile.density`
- `Profile.specific_heat_capacity`

Often you will modify the following hooks by own implementations or constant attributes:

- `Transport.environment_temperature`
- `Transport.cooling_water_temperature`
- `Transport.convection_heat_transfer_coefficient`
- `Transport.cooling_heat_transfer_coefficient`
- `Transport.relative_radiation_coefficient`
- `RollPass.roll_temperature`
- `RollPass.contact_heat_transfer_coefficient`

Transports

`Transport.environment_temperature` The temperature of the environmental atmosphere T_∞ for convection and radiation. The default implementation returns 293.15 K.

`Transport.cooling_water_temperature` The temperature of cooling water T_W for water cooling. There is no default implementation, meaning that

`Transport.convection_heat_transfer_coefficient` The transfer coefficient for convection α_K. The default implementation returns $15\,\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}$.

`Transport.cooling_heat_transfer_coefficient` The transfer coefficient for water cooling α_W. The default implementation returns $150\,\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}$.

`Transport.relative_radiation_coefficient` The relative radiation coefficient for cooling by radiation ε_R. The default implementation returns 0.8.

`Transport.temperature_change_by_convection` The temperature change of the profile due to convection. The default implementation follows the term in described above. It returns 0 if the `environment_temperature` hook returns `None`.

`Transport.temperature_change_by_cooling` The temperature change of the profile due to water cooling. The default implementation follows the term in described above. It returns 0 if the `cooling_water_temperature` hook returns `None`.

`Transport.temperature_change_by_radiation` The temperature change of the profile due to radiation. The default implementation follows the term in described above. It returns 0 if the `environment_temperature` hook returns `None`.

`Transport.temperature_change` This hook represents the total temperature change ΔT. Per default it returns the sum of `temperature_change_by_convection`, `temperature_change_by_cooling` and `temperature_change_by_radiation`.

`TransportOutProfile.temperature` This hooks represents the temperature of the outgoing profile. Per default it returns the sum of `transport.in_profile.temperature` and `transport.temperature_change`.

Roll Passes

`RollPass.roll_temperature` The temperature of the working rolls T_R for roll contact heat transfer. The default implementation returns $293.15\,\mathrm{K}$.

`RollPass.deformation_heat_efficiency` The efficiency of heat generation by deformation η. The default implementation returns 0.95.

`RollPass.contact_heat_transfer_coefficient` The transfer coefficient for roll contact heat transfer α_C. The default implementation returns $6000\,\frac{\mathrm{W}}{\mathrm{m^2 K}}$.

`RollPass.temperature_change_by_contact` The temperature change of the profile due to roll contact within the roll gap. The default implementation follows the term in described above. It returns 0 if the `roll_temperature` hook returns `None`.

`RollPass.temperature_change_by_deformation` The temperature change of the profile due to deformation within the roll gap. The default implementation follows the term in described above. If the roll pass provides a `deformation_resistance` (k_W) attribute or hook, this value is used, otherwise `mean_flow_stress` (k_f).

`RollPass.temperature_change` This hook represents the total temperature change ΔT. Per default it returns the sum of `temperature_change_by_contact` and `temperature_change_by_deformation`.

`RollPassOutProfile.temperature` This hooks represents the temperature of the outgoing profile. Per default it returns the sum of `roll_pass.in_profile.temperature` and `roll_pass.temperature_change`.

Profiles

The plugin specifies two hooks on `Profile` meant for material data: `density` and `specific_heat_capacity`. The default implementations throw solely errors, so you have to provide your own, or at least to define constant attributes on the initial profile instance.

Report

The plugin extends the HTML report with implementations of `pass_properties` and `transport_properties` adding the distinct temperature changes. A `sequence_plot` is also implemented showing the temperature progression along the pass sequence.

Export

The plugin extends the report with implementations of `columns` adding the `unit.in_proile.temperature` and `unit.out_proile.temperature`.