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CALCULATION OF HEAT TRANSFER COEFFICIENTS

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In forced-convection furnaces for reheating Al-alloys, convective heat transfer mechanism dominates. Al-body temperature prediction model uses measured furnace temperature as boundary condition. To calibrate such model, a convective heat transfer coefficient *h* is to be determined. Optimization technique is used here to determine *h* for every measured temperature sample so that measured temperatures match calculated, supposing radiative heat transfer coefficient constant and neglecting conductive heat transfer. Obtained *h* stably converges during normal reheating conditions. The obtained model is 4-fold cross-validated and obtained Root Mean Square Error of whole reheating profiles are [7,7; 20,4; 10,4; 12,5] °C.

Key words: Al-body, convective heat transfer, forced-convection furnace, mathematical model, measured temperatures

INTRODUCTION

In aluminum and steel industry, metal reheating takes place for hot deformation purposes, recrystallization, various heat treatments etc. For massive production dominate directly or indirectly gas fired furnaces, where electrically heated furnaces are used for smaller furnaces and especially for higher temperatures above 1300°C. The temperature course of reheating, duration, final temperatures and similar temperature / time domain characteristics define conditions metals must undergo to bring it to a desired microstructural state. The closer the temperature / time course of metals is known, the narrower is the desired microstructural state of the metal [1-6]. On the other hand, more precise temperature / time course of metals can be used for various process optimizations: energy consumption, scale loss minimization, decarburization depth, desired microstructure, grain size minimization etc. [2], [6-8]. Contact-free metal temperature measurements via thermal cameras or pyrometers are widely used both as permanent or occasional measurements. But in some cases mathematical models offers better accuracy or simpler handling, since temperature calculation can be automated.

Such real-time models require measured temperature boundary conditions [4], [7-8]. On the other hand, such models need also defined heat transfer conditions: radiative, conductive and convective. Probably the most common way of calibration of such models is to concurrently measure temperature on one or more places in the desired reheating bodies as well as boundary temperature(s) of the reheating metal surroundings. Thermal dependent heat conductivity and thermal capacity can be obtained by measurements or by calculation. The only left parameters for calibration of such models are then heat transfer coefficients or total heat transfer.

In forced convection furnaces, which are typically used for reheating aluminum alloys, convective heat transfer dominants at typical temperatures to about 550 °C, where radiative heat transfers adds about 2-5 % of total heat transfer [7]. Geometrical configuration of these furnaces is usually designed in a way that minimizes conductive heat transfer and mechanical damage of Al-coils. In the paper we present example of convective heat transfer calculation for 300 l laboratory scale forced convection furnace used for recrystallization annealing of Aluminum alloys for inspections purposes. In this case, concurrent temperature measurements of air in the furnace as well as temperature measurements in various Al bodies reheated in the furnace are taken. Thermal conductivities and heat capacities are obtained by JMatPro® software. Radiative heat transfer coefficient was estimated and set constant, while conductive heat transfer is due to configuration negligible. The remaining convective heat transfer is calculated, so that measured body temperature matches calculated.

MATHEMATICAL TEMPERATURE MODEL FOR VARIOUS SAMPLE GEOMETRIES

Heat flux describing above described heat flow is

$$j_i = h(T_{air,i} - T_{Al,i}) + \varepsilon\sigma\,(\tau^4_{air,i} - \tau^4_{Al,i}), \qquad (1)$$

where j is heat flux density, σ is Stefan Boltzmann constant, T and τ are temperatures in °C and K, ε is emissivity of the Al-body and h is convective heat transfer coefficient.

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Since aluminum alloys are highly conductive, for laboratory scale reheating samples of various geometries temperature differences are sufficiently low [9], measured temperature differences within various tested geometries never reached 0,5 °C. Thus we simplify the calculation model and calculate a temperature as single body, where heat conduction to body interior is calculated with discrete equation of first order [8]. Typical sample shapes are either cylindrical or rectangular of various dimensions. Therefore temperature model considers conductive path Δx and surface area of each body separately besides thermal data of body alloy. For cylindrical sample is Δx = d/2 and for rectangular is Δx = a/2.

Equation for iteratively calculate temperature of the body is derived from general heat equation [7] is

$$T_{Al,i+1} = T_{Al,i} + j_i \Delta t A \frac{1}{c_p \rho} - \lambda \Delta t \frac{A}{\Delta x} \frac{1}{c_p \rho} \left(T_{Al,i} - T_{Al,i}^{IN} \right) \quad (2)$$

where j_i is calculated by eq. 1, Δt is sample time, Δx is conductive path of the heat towards interior of the body, A is body surface area, c_p, λ are temperature dependent thermal properties and ρ is density. Temperature of the middle point in the body $T_{Al,i}^{IN}$ is iteratively calculated as discrete first order system equation, for which input is surface temperature $T_{Al,i}$ (Eq. 2) and is thus

$$T_{Al,i+1}^{IN} = T_{Al,i} \left(1 - b \right) + b T_{Al,i}^{IN}, \quad (3)$$

where b is discrete-time time constant. For sample time Δt=30 s, for which furnace air temperatures were $T_{air,i}$ taken, time constant b is set to 0,02. Emissivity ε of the body is estimated to 0,18 and kept constant (samples are usually oxidized). Boundary condition ($T_{air,i}$) is delivered every 30 s, equations (1)-(3) are recalculated for next step i+1.

CALCULATION OF CONVECTIVE HEAT TRANSFER COEFFICIENT

Assuming constant ε emissivity of the observed body, neglecting conductive heat transfer mechanism, one can explicitly determine dominating convective heat transfer coefficient. Note that, proposed calculated convective heat transfer coefficient is neither constant over body surface nor it is bias-free (neglected conductive losses and estimated radiative heat transfer). Since both terms are small enough compared to the dominating convective heat transfer, it can be determined so that measured and calculated temperatures match. This way convective heat transfer may partially cover radiative heat transfer inaccuracy (constant ε) and neglected conductive heat transfer. Algorithm for determination of concurrent h is the following. Initial h is estimated and set to 27.

For the h in i-th step $h(i)$, temperature prediction is calculated, difference between calculated and measured temperature is calculated $dT = Tcalc - Tmeas$. If $abs(dT) < dTmax$ then calculated $h(i)$ for i-th step is within prescribed limits and stored for $h(i)$ and as modified initial value for $h(i+1)$. Otherwise, h is modified/adapted in limited loop cycles for positive dT as $h(i)=h(i)-abs(h(i))/8;$ and for negative dT as $h(i)=h(i)+abs(h(i))/8;$ until $dT<dTmax$. This way the model calculated temperature is within $dTmax$ around measured temperature. Simulations tests have shown, that unrealistic model predictions destabilize convergence of $h(i)$, therefore adaptation of $h(i)$ value does not depend on dT. Calculated $h(i)$ is presented on Figure 1 (upper). Difference between calculated and measured temperature is shown on Figure 1 (lower) and is within set $dTmax$ = 0,1 °C.

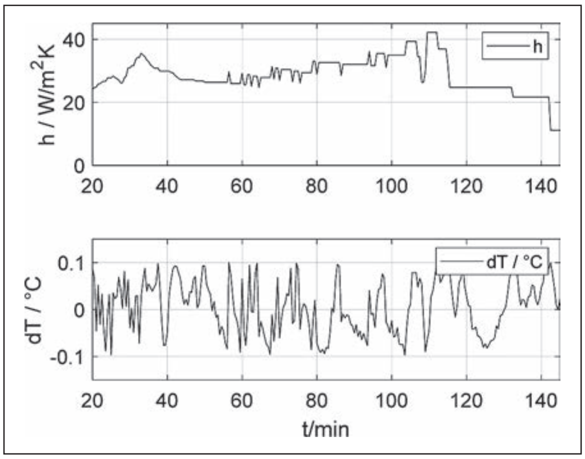

Figure 1 Obtained *h* values along heating profile(upper) and *dT* for the obtained *h*

MODEL VERIFICATION

Obtained mathematical model is k-fold cross-validated for k = 4 independent temperature profile measurements, meanwhile model parameter (convective heat transfer coefficient h) is averaged over all 4 temperature profiles. Note that h is function of temperature difference ($T_{air,i} - T_{Al,i}$). Prediction accuracy is checked with significantly different boundary condition - furnace temperature profiles: reheating time is prolonged and furnace temperature rise is piecewise linear with two different slopes and afterword kept constant. Match between material temperature calculation and measurement profile is measured by Root Mean Square Error (RMSE). Obtained RMSE of whole temperature profiles of 4-fold verification are [7,7; 20,4; 10,4; 12,5] °C. Since model accuracies at steady-state are much better, RMSE for last 20 minutes (steady state) of each profiles were calculated and are [0,92; 2,44; 0,74; 1,09] °C. Match between obtained model prediction and measurement for 3rd and 4th temperature profile is shown on Figures 2, 3.

CONCLUSIONS

The nature of high conductivity of Al-alloys enables use of simple models for Al-body temperature calculation. Since inner structure of the model is of the lumped-

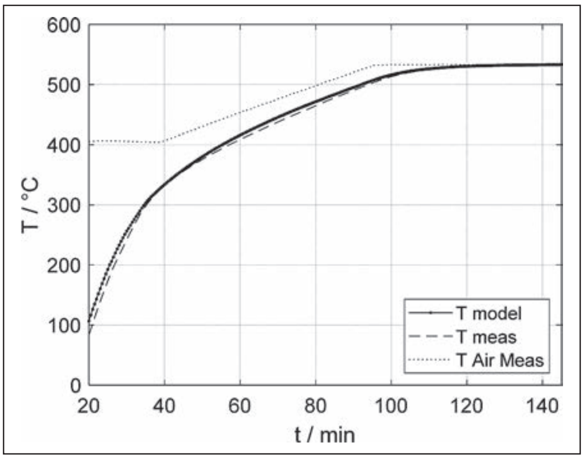

Figure 2 Model prediction temperature profile and 3rd measured profile together with furnace temperature, RMSE =10,1 °C

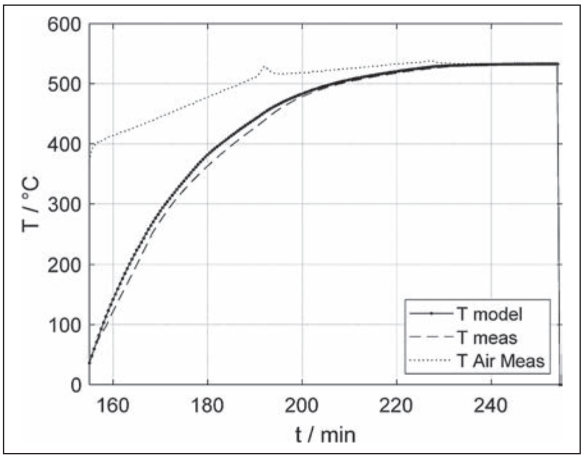

Figure 3 Model prediction temperature profile and 4th measured profile together with furnace temperature, RMSE =12,3 °C

parameter type it allows very fast calculation of temperature profile, what is excellent for model predictive control applications. The proposed model for temperature calculation exhibits acceptable steady state RMSE accuracies below 2,5 °C. Convective heat transfer coefficient is calculated by minimization of difference between measured and calculated temperature of Al-body.

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