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Flatness Based Inductive Reheating of A356 Billets into the Semi-Solid State

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Abstract. An important step in the processing of semi-solid metals is the inductive re-heating of the feedstock material. The heating should lead to an uniform billet temperature in order to obtain good forming results. The billet is supposed to be heated to the target temperature as fast as possible and at the same time it must be guaranteed, that the outer area of the billet does not melt prematurely. Conventionally the open-loop trajectories consist of simple power over time diagrams and are generated by extensive experiments. By using an open-loop control scheme it is possible to chose a desired trajectory for the middle axis temperature of the billet which respects the given constraint on the heating process. By taking advantage of the flatness property of the system, an open loop trajectory for the coil current can be calculated which ensures the desired behavior of the axis temperature. The shape of the trajectory is determined by the shape of the desired trajectory and the temperature dependent material properties, which have to be known with the needed accuracy. The losses of the converter and induction coil are estimated online so that the induced power is known. The trajectory ensures that the billet is heated to a temperature just below the solidus temperature without overheating of the billet's surface and with a very homogeneous temperature distribution. The Experiments have been conducted using A356 aluminum alloy.

Introduction

The semi-solid process chain consists of the heating of the feedstock material followed by the forming step. The result of the forming step depends heavily on the quality of the prior heating step. The billet is supposed to be heated to the target temperature as fast as possible and at the same time it must be guaranteed that the outer area of the billet does not overheat and begins to melt prematurely. Usually the open-loop trajectories are generated by many experiments in order to achieve the desired state of the billet. By exploiting the flatness of the system [1], it has been shown that the temperature distribution within the billet is only dependent on the billet's axis temperature and the induced power [2]. By using these results and considering the nonlinear temperature dependency of the material properties, trajectories for the coil current and for the induced power will be calculated and evaluated by experiments in this paper.

Trajectory Calculation

In [2] it has been demonstrated that the temperature distribution within the billet is only dependent on the billet's axis temperature and the induced power. Without recapitulating the derivation in detail, the main results should be presented in the following as long as it is needed for the understanding of the succeeding parts. In this paper the following differential equation has been derived by using the flatness of the system:

$$\sum_{i=0}^{\infty} c_i \overset{(i)}{g}(t) = \sum_{i=0}^{\infty} b_i \cdot \overset{(i)}{\vartheta}(0,t) - \vartheta_e; \quad b_0 = 1, b_n = \left(\frac{1}{a}\right)^n \cdot \left(\prod_{i=0}^{n-1} k_i\right) \cdot \left(\frac{{r_b}^{2n}}{(2n)!} + \frac{\lambda}{\alpha}\frac{{r_b}^{2n-1}}{(2n-1)!}\right), n \geq 1.$$
$$c_m = \frac{1}{\lambda}\left(\frac{1}{a}\right)^m \cdot \sum_{i=m}^{\infty} f_{d,2i} \cdot \left(\prod_{j?i}^{m+1} k_i\right) \cdot \left(\frac{{r_b}^{2(i+m+1)}}{(2(i+m+1))!} + \frac{\lambda}{\alpha}\frac{{r_b}^{2(i+m)+1}}{(2(i+m)+1)!}\right), m \geq 0. \tag{1}$$

Whereas $\vartheta(0,t)$ denotes the billet's axis temperature and $g(t)$ equals the power generating term. The following abbreviations have been used in the above formula:

$$a = \frac{\lambda}{\rho c_p}; \quad k_i = \frac{2i+1}{2i+2}; f(r) = \left|\frac{J_1\left(\sqrt{-i\cdot 2}\, r_b / \delta\right)}{J_0\left(\sqrt{-i\cdot 2}\, r_b / \delta\right)}\right|^2; f_{d,2i} = \left.\frac{d^{2i} f(r)}{dr^{2i}}\right|_{r=0}.$$
$$g(t) = \frac{N_c^2}{\kappa \delta^2 L_c^2}\hat{I}_c^2(t); \quad \delta = \sqrt{\frac{2}{\kappa\omega\mu}}. \tag{2), (3}$$

λ is the thermal conductivity, c_p the heat capacity, ρ the density, κ the electrical conductivity and μ the magnetic permeability of the used aluminium alloy. α equals the heat-transfer coefficient for free convection, ω is defined as circular frequency, δ is the resulting penetration depth, N_c represents the number of coil windings and L_c equals the coil length. J_1 and J_0 are the modified Bessel functions of first and zero order. Inserting the desired behavior of the axis temperature $\vartheta(0,t)$ into equation (1) delivers the trajectory for $g(t)$, which can be used to calculate the trajectory for the coil current.

Strictly speaking these equations are valid for constant material parameters only, an assumption that does not hold true since all material properties are temperature dependant. If one regard the movement of the system along a desired trajectory, one obtains a time varying system because of the temperature dependant material properties. As long as the transition speed is slow compared to the change of material properties, these equations can be used. Thus it is possible to solve the equation (1) with constant parameters and to substitute the temperature dependant material properties in the solution only.

Control trajectories. The obtained trajectory $g(t)$ must be realized at the induction furnace which exhibits the converter power as manipulated variable. Starting form the definition of $g(t)$ the trajectory for the coil current $I_c(t)$ can be calculated. It is also possible to calculate the power induced into the billet $P_b(t)$ by integrating the volume power density. This leads to the following formulations:

$$I_{c,rms}(t) = \frac{L_c}{N_c}\sqrt{\frac{g(t)}{\mu\omega}}; \quad P_b(t) = \pi \cdot h_b \cdot \delta \cdot r_b \cdot g(t) \cdot \left(\frac{\sqrt{2} r_b}{\delta} - \frac{1}{2}\right) \tag{4), (5}$$

These trajectories can be realized directly if the coil current and induced power are known online. In this case a simple subordinate PID controller can be used to adjust the convert power so that the trajectories for $I_c(t)$ and $P_b(t)$ are matched.

The inductor coil current can be measured directly whereas the induced power must be estimated from plant data. The losses of the induction furnace are mainly frequency dependant and can be expressed by an ohmic resistance R_0 which is adapted to the actual value of the resonant circuit frequency. The ohmic resistance can be determined by an idle run of the induction furnace at the idle frequency f_0, i.e. coil without billet, and then dividing the converter power by the square power of the coil current. The induced power $\widetilde{P}_b(t)$ can be estimated online by using the following equation:

$$\widetilde{P}_{loss}(t) = R_0 \cdot I_c^2(t) \cdot \frac{f}{f_0}; \quad \widetilde{P}_b(t) = P_{rc}(t) - \widetilde{P}_{loss}(t) = P_{rc}(t) - R_0 \cdot I_c^2(t) \cdot \frac{f}{f_0}. \tag{6), (7}$$

By evaluating equation (7) with online data, a subordinate PID controller can be used to control the induced power $\widetilde{P}_b(t)$ and to follow the calculated desired trajectory from equation (5).

Experiments

The experiments have been conducted using an induction furnace consisting of a converter and an inductor coil with optimized geometry, so that the axial temperature field remains homogeneous throughout the complete heating cycle [3]. A356 aluminium alloy billets with a height of 150 mm and a diameter of 76.2 mm were heated in the upright position. The material properties were taken from literature [4] and have been approximated with sufficiently smooth functions to be used in conjunction with the solution to equation. (1), see fig. 1.

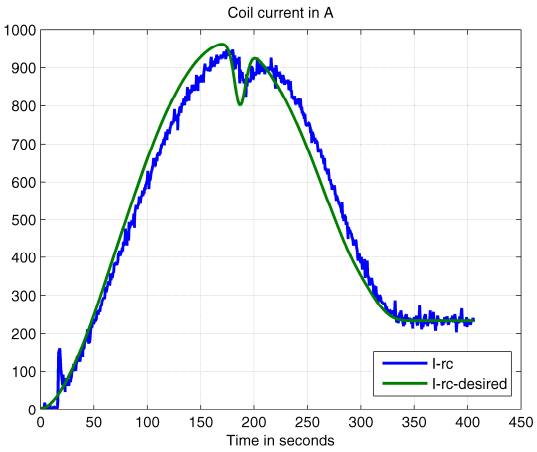

Figure 2: Desired and actual coil current course

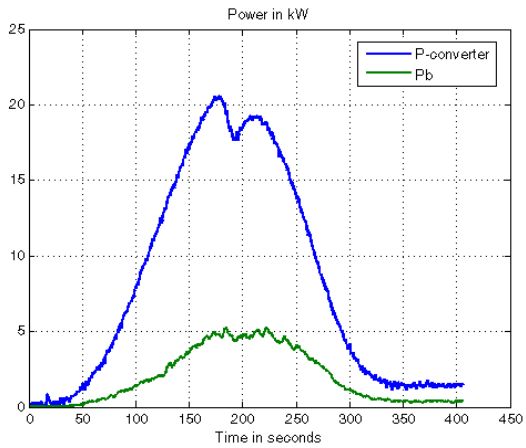

Figure 3: Converter power and induced power

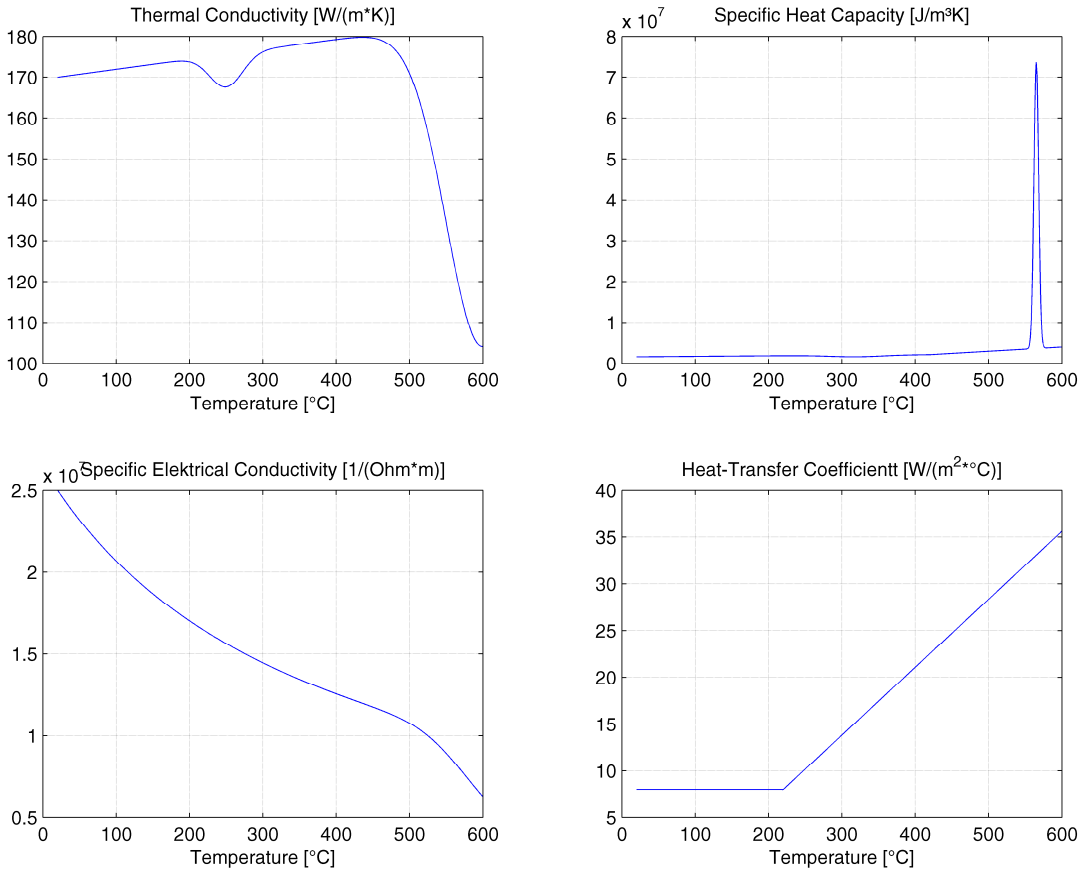

Figure 1: Course of the use approximated material properties.

Thermocouples have been attached to the center and the edge of the billet in order to gain information about the temperature distribution. Figure 2 shows the calculated trajectories for the coil current $I_c(t)$ and the achieved coil current controlled by a standard PID controller. There is still a lag between the desired and the actual value because the PID controller is not tuned perfectly. Figure 3 shows the converter power and the online calculated induced power $\widetilde{P}_b$. The resulting temperature course of the axis and surface temperature is showed in figure 4 with the desired temperature course. There is still a significant deviation which is caused by the bad performance of the coil current controller and by the heat capacity of the material which is assumed too lowly. The achieved results are very good, taking into consideration that only literature data have been used for the material properties. By adjusting the material data accordingly these deviations will disappear.

The steady state temperature shows a very small difference between the surface and the axis temperature. An open-loop control scheme will always have some deviations but it is possible to heat the aluminium billets just below the solidus temperature with great homogeneity.

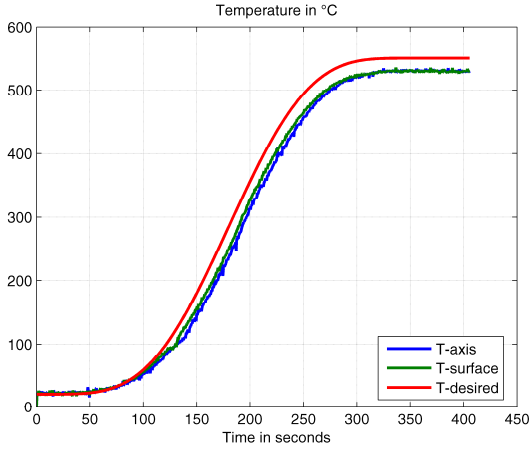

Figure 1: Desired and actual temperature course

Summary

It has been shown that by using open-loop control technique it is possible to reheat a aluminium billet to the target temperature without many trial and error experiments. The material properties have to be known with sufficient accuracy in order to achieve good trajectory following. For future works an automated identification of the material properties is planned, so that these properties are identified by using a single heating experiment with constant converter power.

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