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A model for aluminium quenching process optimal setup

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Abstract: The quenching aluminum process is introduced and its complexity associated to setup optimization and closed loop control reviewed. Additionally the basics about a physical mathematical model together with the necessary optimization strategies and some enabling optimization technologies are here summarized.

Keywords: Temperature control, modeling, aluminum production.

1. INTRODUCTION

The rolled aluminium sheet and plate is used extensively as the 'raw material' in a wide range of manufacturing industries (e.g. transportation, aerospace, automotive, rail, marine), containers and packaging, building and construction, common specialities like litho, heat exchangers, cookware, etc. Aluminium rolling can be designed to achieve the target gauge with an attractive combination of mechanical properties compared to other process routes thanks for the high strength and, at the same time, the high formability. Additionally aluminium can be engineered to achieve a range of critical properties like high thermal conductivity, good corrosion resistance, high electrical conductivity, bright appearance, non-toxicity, and full recyclability.

The quench process, see Liscic, B., H. M. Tensi, L.C.F. Canale, G.E. Totten (2010), is part of heat–treatment where the temperature of the material after casting is rapidly dropped to near room temperature to trigger strength enhancement mechanisms, see Sheppard, T., A Jackson (1997). In the quench of flat products of aluminium alloys, the piece is sprayed continuously with a coolant fluid, typically water with a specific temperature, to reach the desired target temperature.

The quench process is controlled by a suitable automation and, in particular, a Process Control System (PCS) that contains a model-based procedure for the generation of working set points (a.k.a. setup) and for control purposes.

The paper is organised as follows. In Section 2 the quenching process is described, we highlight its complex features and we explain why it is important to develop a model-based solution. Section 3 is dedicated to the introduction of the optimisation technologies necessary for setup computation whereas Section 4 is dedicated to the real-time control issues. Finally some ending concluding remarks are proposed in Section 5.

2. PROBLEM SETTLING

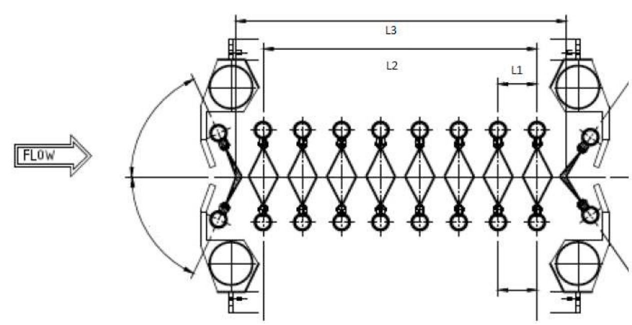

Fig. 1. Structure of a typical quenching machine for aluminium.

The objective of the model is to predict the material temperature at the exit side of the machine taking into account the actuator set-points, the incoming material temperature, the material thickness, the material travelling speed and the sprayed coolant temperature. Moreover the physical model will be exploited in the context of an optimisation toolbox in order to select the actuator statuses that allow achieving the desired target temperature at the exit side of the quench process.

In the most conventional configuration of such type of processes, the actuators are represented by:

1) a water pump that feeds a set of coolant headers installed along the length of the machine (see Fig. 1)

2) the headers themselves that can be in open or closed status.

3) the coolant temperature can be considered as an additional actuator but not in the context of a real-time controller due to the very long time-constant associated to it. For this reason in the following we will not consider it as a variable to be optimised but as a pre-defined parameter.

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Between the coolant headers it is worth distinguishing from the others those installed at the beginning and at end of the machine referred to as *wipers*. These have a special orientation since they spay coolant in the direction of the machine in order to constrain the coolant to stay confined therein.

The cooling efficiency of the machine is conditioned by important geometrical factors like the distribution distances of the coolant headers (see Fig. 1 – the parameters L1, L2 and L3 represent important design dimensioning figures) or the characteristics of the nozzles installed (see Fig. 2).

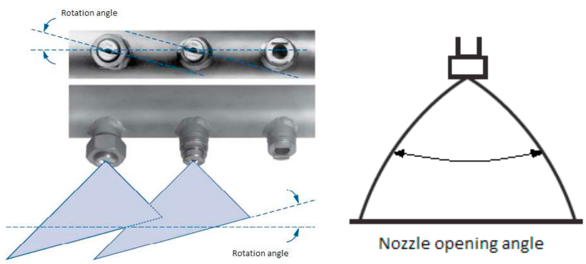

Fig. 2. Definition of nozzles rotation and opening angles.

The model uses the knowledge of all these geometrical parameters and the possible flow rates through the nozzles.

In order to estimate the effect of the quenching to the material, the model uses a transient explicit finite volume calculation method where the material is divided into sections down the length and layers through the thickness. The boundary conditions for the model are the *coolant temperature* and the *material to coolant Heat Transfer Coefficient* (HTC). These coefficients can be different for the top and bottom surfaces. They depend on the spray intensity (flow rate per unit area) and on the local strip surface temperature. The HTC calculation is performed every time-step because the local surface temperature can change very rapidly. These predicted HTC values must apply over a wide surface temperature range including boiling and single phase heat transfer.

Because the local HTC can be very high, particularly when the coolant passes through the nucleate boiling range, the model needs to include an iterative calculation of the coolant temperature rise and the mean local HTC. Consequently, the local variation in coolant temperature represents an output of model together with the material temperature. The overall coolant temperature rise is also calculated based on the overall heat transfer and the overall coolant flow.

The main output of the model on which we will focus in the following part of the paper is represented by the metal temperature change as it passes though the quench, including the variations through the thickness of the strip.

The model will have access to the nominal flow rates at a specified pressure for the nozzles and to the pressure range that applies to the nozzle based on the minimum and maximum pump speeds.

2.1 The optimisation algorithm

An algorithm is used to determine how many headers in each section are to be enabled and the necessary cooling flow-rates for each section to achieve the target exit temperature. The algorithm is designed to use as many spray sections as possible within the quench machines operational limits in order to minimise any thermal stresses which could encourage material buckling.

2.2 Target temperature

Every quenching section is designed around a set of input strip parameter values that include the material mass flow (material travelling speed times material thickness), the input temperature and the temperature drop that needs to be achieved. The quenching section is designed by specifying the number of spray headers needed to achieve the largest temperature drop for the range of incoming material characteristics.

When a large temperature drop through the quench is required, then most of the spray headers will be switched on and the strip will be sprayed over the quench length. Because many headers are used, the flow rate to all the headers can be adjusted together and the sensitivity to variations in the value of the incoming strip parameters can be accommodated. Conversely, if a small temperature drop is required then only a small amount of headers is to be kept in open status.

3. SETUP PROCEDURE

The quenching machine is to be regulated to the working points before the piece enters it, in order to immediately reach the desired targets at the head-end of the strip.

The setup calculation task is in charge of executing the optimisation of the set points according to the geometry of the quenching machine and taking into consideration the primary information about the piece (PDI), the process rules restricting the specific process requirements and the actual speed and temperature of the material (see Fig. 3).

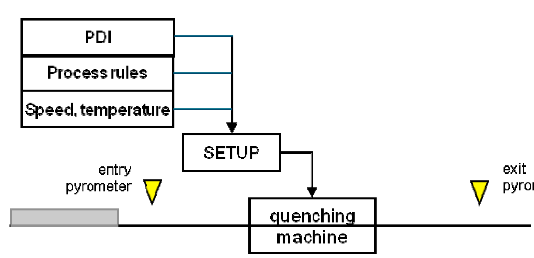

Fig. 3. Setup scheme of the quenching machine.

The setup computation is a complex problem due to the following issues:

- the problem has a Mixed Integer (MI) nature (see Richards, A. and J. How (2005)) since the control variables are represented also by logic enabling conditions (i.e. the wipers and header enabling statuses) and one real variable (i.e. the coolant mass-flow realised by the pump);