ANALYSIS OF SOLID-LIQUID TRANSITION IN AZ31 MAGNESIUM ALLOY IN TRC PROCESS USING THERMOCOUPLES AND OFFLINE DIGITAL-TWIN

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Abstract

With increasing interest in lightweight construction and cost-efficient sheet production methods, the twin roll casting of non-ferrous metals is constantly developing, due to the combination of several different process steps into one process. However, its challenge is the impossibility of direct recording of important process parameters such as temperature and pressure distribution in the rolling gap, in order to control product properties, due to the difficult process conditions. This article will discuss asolution to transform the twin roll casting process into a process that can controls product properties using a softsensor with additional inline measurements for temperature and pressure at the surface of the work rolls and a digital twin. The digital twin is used to predict correlations between the entities at the roll surface and the material properties in the bulk of the strip. The model used in this article is an extension of the layer model proposed by Schmidtchen and Kawalla based on the classical elementary theory of plasticity, which aimed to model the heterogeneous deformation behavior during flat rolling. Its great advantage compared to other simulation methods is a much lower computational effort. The actual extension as casting-rolling tool as proposed by Weiner et al. combines a viscous and a solid region for each layer in one tool. Experimental results were obtained that allows the direct correlation between the shape of temperature distributions and the length of the fully solidified part Ld within the roll-casting zone. This length correlates directly to the effective total equivalent strain. The static recrystallization in a subsequent heat treatment process is improved and results in a better formability of the magnesium strip with increasing strain.

Keywords: Twin roll casting, layer model, rolling, soft sensor, digital twin

1. INTRODUCTION

The advantage of the continuous casting process is the combination of solidification and forming in one process step, which results in a formed casting structure [1]. This favours the subsequent behavior of the SRX (explain SRX) and thus the mechanical properties during further rolling [2-6]. However, due to the very large number of input variables in the process, it is very sensitive to fluctuations in the individual output variables. Therefore, in order to control them accurately, it is necessary to use sensors, which measure additional measuring signals, as well as process models, which enable simulation of the process using the same parameters [7-8]. So far, process models have been used for a basic understanding of what processes occur in the rolling gap and how the crystallization front proceeds [9-11]. For this purpose, the model developed in [8] was used. Which is a fast simulation tool based on a coupled visco-plastic layer model, on the one hand, a better interpretation of the correlation between the variables measured at the roller surface and the process conditions in the rolling gap was obtained. On the other hand, the model adapted to the twin roll casting process can be used to generate offline training data for the control algorithm. However, the comparison between simulation and experiment is problematic due to the lack of complete data signals from the solidification and rolling zone itself in the model used, which are mostly adjusted based on single experimental data. There are few reliable experimental data on the solidification process. It has already been demonstrated that strip casting has the advantage of refining intermetallic compounds that otherwise exist as harmful coarse particles in conventionally processed alloys. The fine and uniformly dispersed particles retard the movement of dislocations, increasing strength, while at the same time blocking dislocations, thus altering slip systems by lateral sliding, thus maintaining good ductility. In addition, fine particles inhibit grain growth during high temperature heat treatment. This paper presents observations on how measuring the surface temperature of the rollers during the Twin Roll Casting (TRC) process alone, aided by a layer model, allows us to observe how the crystallization front moves as its temperature changes. In the planned later addition of a piezosensor to the sensor, it will allow an even more accurate determination of how pressure in the rolling gap affects this. So, using the data from the sensor, together with the results of simulations, a soft sensor can be prepared, which at a later time would serve as a digital twin of the continuous casting line. This would allow live control of the process parameters, which would already be known from previous processes and simulations, in order to determine where the crystallization front is. This is important because the closer it is to the nozzle, the greater the deformation, which affects the microstructure and thus the parameters of the resulting material.

2. INTEGRATION OF SENSORS FOR MEASUREMENT IN THE ROLLING GAP OF THE CASTING ROLLES

Sensor integration in TRC is particularly challenging due to the high thermal and mechanical boundary conditions. From previous simulations of the twin-roll casting process, it is known that normal stresses of up to 400 MPa and temperatures of up to 650 °C occur at the surface of the roll [8]. Considering the further constructive boundary conditions resulting from the split, internally cooled roll core, direct placement of the sensor on the surface is not possible. As a result of cooling, the temperature drops rapidly inward. Depending on the possible operating temperature, different sensor principles must be integrated at different depths in the roll. Since the knowledge of the maximum temperature as a function of the roll surface is essential for the sensor design, a thermal-transient simulation was performed and the effect of the cooling water temperature on the measured temperature gradient in the roll coat was estimated using the finite element method.The shell was subjected to a constant temperature of 630 °C around the entire circumference, at a maximum rolling speed of 2.2 m/min and a cooling water temperature of 30 and 60 °C. Temperature curves were obtained as shown in **Figure 1**, which shows, that the rapid temperature rise can be detected independently of the cooling water temperature.

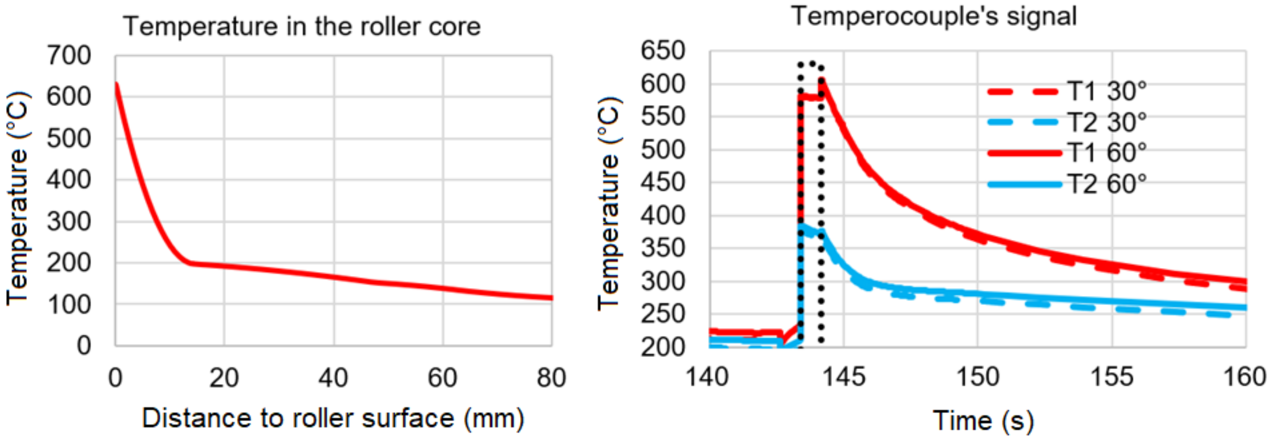

Figure 1 Results of the Finite Element thermal calculation

Basing on this data and literature [12], the piezosensor was used, as shown in **Figure 2**, which can be externally inserted. This avoids the need to fabricate a new coat and connect it to the roller core, since it cannot be removed without causing damage. Additionally, sensor wires can be routed through an additional channel inside the roll. The pin (red in **Chyba! Nenalezen zdroj odkazů.**) is routed to the surface of the roller and measures pressure over a small area. The thermocouples and the pressure sensor are located at the same angular position of the roll and detect the process condition without a time offset. The sensor inserts, which is mounted externally, must be sanded to a roller surface. **Figure 2** shows the different stages of sensor mounting. After grinding, the uppermost thermocouple is only about 0.25 mm below the surface and is thus in very close proximity to the active point. The sensor signals are detected on the roll and transmitted wirelessly to the dSpace system. In the rotary roller, energy is supplied by a battery, which enables operation for 12 hours.

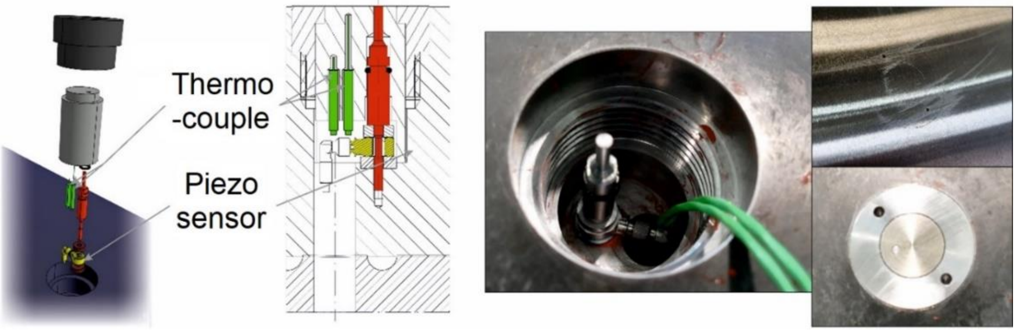

Figure 2 Sensor construction

The soft sensor shown in **Figure 3** Soft sensor used for controlling of band properties during casting rolling is used to further control the process. For this purpose, intermediate variables such as the position at the solidification front (L_D), calculated by the angle α (which runs from the beginning of contact of the molten material to the exit of the rolling gap), can be used in subordinate control loops. In performing such a property check, a stepwise implementation and validation of the control and soft sensor is possible.

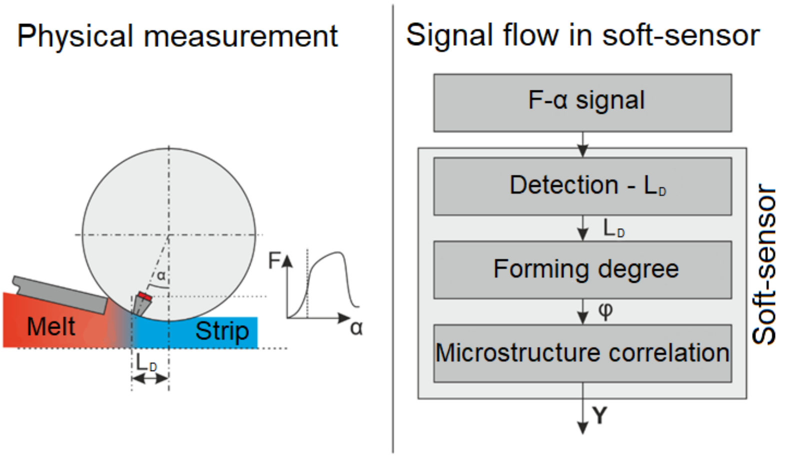

Figure 3 Soft sensor used for controlling of band properties during casting rolling

3. BUILDING A DIGITAL TWIN IN THE FORM OF AN EXTENDED LAYERED MODEL

The Institute for Metal Forming (IMF) layer model (**Figure 4**) was used to correlate the initial measurement results with the strip parameters. The most important advantage of the model is the extension of the classical elementary elastic-plastic theory to the viscous model. Thus, two main regions can be distinguished, the red region between x_{00} and x_{01} is the viscous region where the material is melted and modeled as a viscous fluid according to Newton's law. Different shades of red represent solidification states, from dark to light they are liquid, mushy and solidified states. The blue zones represent the fully elastic-plastic model. In the layer model for the TRC process, the material is divided into individual layers parallel to the rolling direction, which are subject to local solidification, strength development, and deformation conditions in the solid state. The partial approach consists of a viscoplastic design core for the liquid and partially solidified region and an isotropic-elastic-plastic design core for the solidified state. The solution is the same as in classical elementary theory, except that models are created individually for each layer. Most simulations currently used for this purpose were based on the finite element method due to the complexity of the problem. However, the finite element method requires too much computational time to generate larger data variants, especially for nonlinear problems due to the large number of iterations. For highly nonlinear problems, computation times of several hours to several days may occur. The Freiberger layer model requires an order of magnitude less design time for conventional rolling processes.

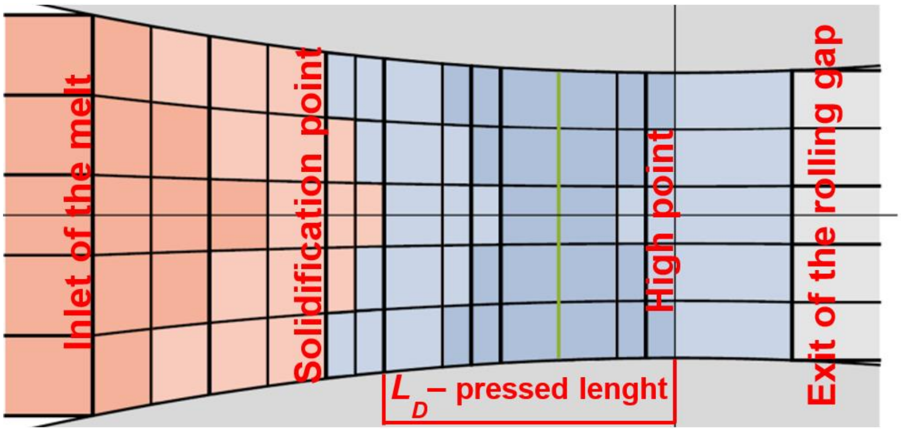

Figure 4 Modeled schematic representation of the roll gap during twin roll casting of AZ31

The most important input parameters of the layered model are: Number of layers, casting bath temperature, nozzle setback, roll radius, roll speed and roll temperature. In addition, parameters such as friction values, initial material deformation and fluid pressure must be defined. The material data of the tested material AZ31 was used as the thermo-mechanical properties. With these inputs, the layer model can provide data such as L_D of course, but also temperature distribution, pressure etc. as well as rolling force and torque for the rolls used.

There is a need to combine both models together. The solution of the differential equations begins with the location at the nozzle outlet, the point of first contact between the molten material and the rollers, denoted x_{00}. For the first condition, the initial pressure gradient value k_0 is the appropriate parameter to fit the velocity profile. k_0 determines the curvature of the velocity profile at point x_{00} and must be chosen so that at point x_{01}, the velocity at all points in the y direction is constant. Therefore, to calculate equivalent viscosity of the layer η, viscosity of the solid η_s and melt η_l are required along with solidified mass fraction f_s (equation 1):

$$\eta = \eta_i + \exp\left[\ln\left(\frac{\eta_s}{\eta_l}\right)\cdot f_s\right] \quad (1)$$

where η_i - viscosity of current the layer

In contrast, f_s is the free variable of the solved model. Depending on the temperature T_i of the current layer, f_s can be 0 for the liquid state and 1 for the solid state. An approach is needed that describes the solidification progress as a function of temperature (equation 2). A simple polynomial function is used here. This function approximates the lever rule and therefore also assumes an equilibrium state of the system. In general, however, any approach that yields the functional relation $f_s(T)$ based on the differences between the absolute

T and solid layer T_s temperature, along with liquid T_l and solid layer temperature, respectively should be implementable.

$$f_s(T) = 1 - \left[\frac{T-T_s}{T_l-T_s}\right]^2 \qquad (2)$$

A heat balance in modified enthalpy form is used for solidification calculations to account for the heat of transformation corresponding to the transformed phase fractionswithin the stationary state. In this case the material parameters as density ρ, heat capacity c_p and conductivity λ, heat transfer coefficient α_{th}, together with layer thickness *h* and velocity in rolling direction must be known v_x. The temperature and heat flux distributions of the layers are modeled by the finite difference method in the vertical direction to obtain differential equations for the temperature *T* and the solid fraction f_s of each layer.

$$\rho c_p h_j V_{xj} \frac{dT_j}{dx} + q_S \, \rho \, h_j V_{xj} \frac{df_{sj}}{dx} = 2\lambda \frac{T_{j-1} - T_j}{h_{j-1} + h_j} + \alpha_{th}\left[T_{j-1} - T_j\right] \qquad (3)$$

where: q_s - heat generation by solidification per mass unit

Equation (3) gives an example for the outer layer to the top roll. For the outermost layers (indices *j* = 0 and N_L which is number of layers) there is a different approach than for the transfer between material and rollers. Furthermore, $\alpha_{th}$is the heat transfer coefficient q_s is heat of solidification, and f_{si} is defined by (2).

4. COMPARISON BETWEEN LAYERED MODEL AND IN-PROCESS MEASUREMENTS

Figure 5 shows a comparison of the strip surface temperature from the layered model and the measured roll temperature just below the roll surface. By comparing the start of the L_D point from the simulation with the jump in temperature of the roll, it can be seen that they start at the same moment, which confirms the correctness of the result from the model. In addition, it can be seen that as the velocity decreases, the L_D point moves towards the nozzle. With the material parameters and temperatures above, it can also be calculated how hot the roll heats up during the process. Based on the layer model, a correlation between rolling speed and solidification point can also be established. The controllability of the process with respect to strip properties is therefore determined by the setting of L_D.

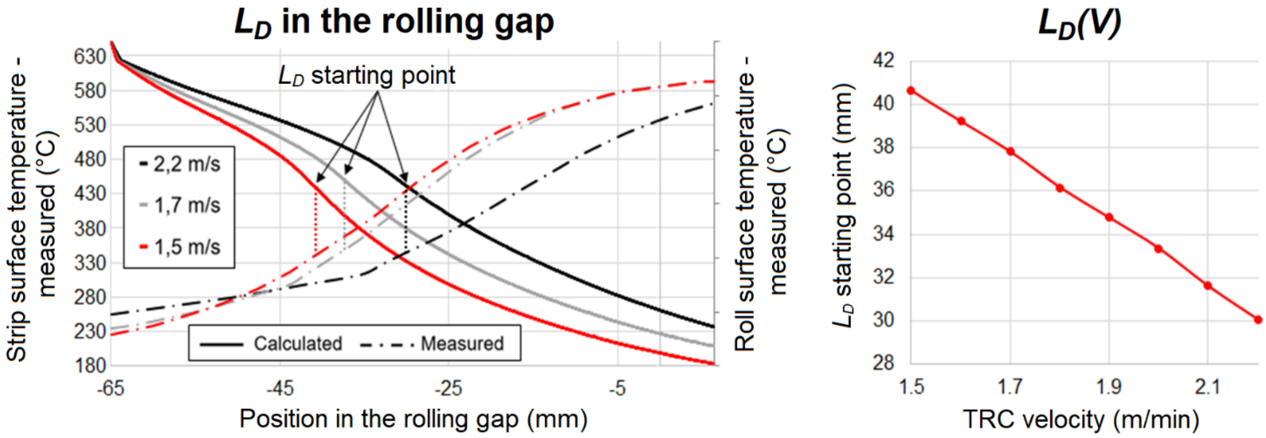

Figure 5 Comparison of results from layer model and measurements from sensor mounted in the roll (left) and correlation between position of solidification front and rolling speed (right)

In orderto control the process, it is important to know how the parameters affect the microstructure. For this purpose, microstructure studies have been carried out based on TRC tests under different process conditions. Depending on the degree of solidification, a maximum deformation of 0.1 can be achieved at a casting speed of 1.5 m/min. At high speeds, the core material is still liquid at the highest point of the rolling gap, and its solidification structure resembles that of a normal casting, such that dendritic structures occur in large numbers. **Chyba! Nenalezen zdroj odkazů.** shows that the grains become increasingly deformed with decreasing rolling speed, which is due to the fact that the stresses increase inversely proportional to the rolling speed. In addition, texture studies showed that AZ31 exhibits an increasing basal texture as a result of the moulding condition with increasing mold, which is undesirable at further stages of moulding. Grain height and length were also measured as part of the microscopic analysis. **Figure 6** shows the relationship between mechanical properties and grain size, as a function of L_D, it can be also seen, that the grains flatten more with decreasing rolling speed. In addition, a tensile test was performed for each speed, which showed that the strength of the material increases with lower speeds. This confirms the above assumptions related to the shape of the microstructure.

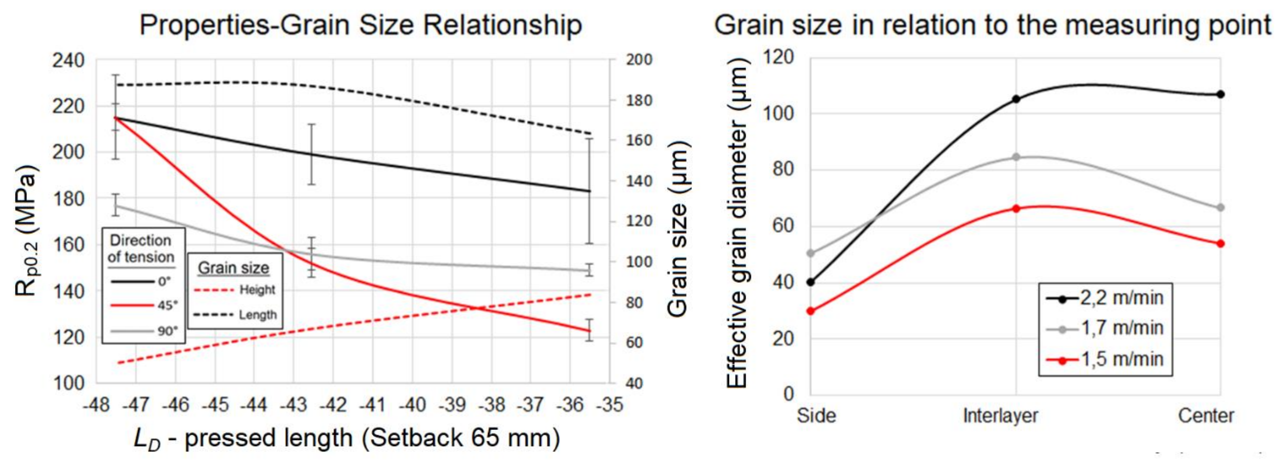

Figure 6 Dependence of averaged grain size and mechanical properties on L_D (left) and average grain sizes depending on the measuring point on the belt

5. CONTROL CONCEPT

Property control requires information about what properties are currently being received. For this purpose, a model can be created that calculates the grain size. The solidification behavior of the alloy is derived from the temperature module of the layer model. The crystallization morphology changes with the temperature gradient and the growth rate of the solidified region. For higher growth rates and lower temperature gradients, isosceles dendrite structures are formed, otherwise columnar dendrites are observed. From the sensory determination of the L_D solidification point from the temperature time course and, in further experiments, from a significant pressure increase, the height at the beginning of the fully plastic formation can be determined

Therefore, a control concept was developed to transform the process into a property-controlled process. In the above process, some of the output variables cannot be measured directly, so in order to control it, a softsensor based on a layer model must be used to calculate these values online. In the next steps, the L_D control is to be fully modeled to determine the parameters of the weight matrix. Additionally, the system will be extended to include dynamic components of the actuators and the process itself. The L_D control will be implemented and validated in the plant. Based on the results of the dynamic behavior of the process, additional sensors will be installed on the roll to more accurately set the L_D observations. The integration of the property sensor at the strip output and the complete implementation of property control represent a transition to a property-controlled casting-rolling process that achieves the desired grain sizes and deformations. The correlation between sensor and properties is to be extended to further microstructure features and their distribution over the strip thickness. As a technologically important variable, tape texture in particular is included here as another control target variable. Without control, it develops in the opposite direction to the grain size development, so that undesirable basic textures develop as the degree of deformation of the casting structure increases. By further refining the digital twin, among other things in the description of the processes in the solidification zone, it should be investigated what property correlations can still be obtained from the signal data in the casting roll gap.

6. CONCLUSION

The most important element of the TRC process of magnesium alloys is to obtain a constant quality with maximum length of the fully solidified cross section. To achieve this the introduction of a property control system was developed, in which the features of the microstructure of the produced strip are controlled by means of a soft sensor. The control strategy is based on the measurement of roll surface temperature, heat flow and normal pressure waveforms and the calculation of the resulting strip properties using a property estimator. With the help of the digital twin, it should be possible to transfer the control strategy to other cast-rolling plants or materials and to generate additional training data for the property estimator. In the given work, the soft-sensor operating conditions and the sensor data required for control in the rolling gap were analysed and compared with results from thermocouples. The correlation between sensor data, L_D and formation is demonstrated. This provides a basis for further design of the required control with respect to strip properties. Furthermore, reliable data from the rolling gap has been determined with which it is able to evaluate the numerical models. The digital twin developed for the TRC process based on the layer model could thus be realistically adapted to the process and can now be used as a digital twin, which will be further developed to later be able to generate training data for the soft-sensor for the TRC process. In this way, it will be possible to control the whole process in real time to obtain the microstructure of the strip and its properties.

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