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Correlation of digital twin and roller surface sensor results for az31 alloy twin roll casting process

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Due to the growing interest in lightweight construction in the automotive and aerospace industries, among others, continuous twin roll casting (TRC) of lightweight metals is constantly expanding. This is due to the cost-effectiveness of the process, as it combines several steps in the production of metal sheets. Due to the nature of the process, the parameters in the rolling gap, such as for example pressure and temperature, are unknown, which significantly affects the ability to understand the phenomena occurring in the rolling gap and thus in the material during rolling. In this work, a key development for a live analysis of the TRC parameters in the rolling gap by means of inline sensors will be presented. Therefore, at IMF Freiberg,

a special rolling gap sensor was mounted in the surface of the TRC roller, consisting of a piezoelectric pressure sensor and two thermocouples measuring the temperature at two different heights, in the same measuring plane. This combined sensor data offers access to the roll surface temperature and the pressure in the rolling gap to be monitored live during the TRC process. The measurements were further supported using a digital twin in the form of a layer model by Weiner et al.. The model used in this work is an extension to the viscous part of the layered model proposed by Schmidtchen and Kawalla, based on the classical elementary theory of plasticity, which aimed to model the non-uniform deformation behaviour during flat rolling. This resulted in a new model, which combines the liquid (as viscous) and solid (as elastic-plastic) regions for each layer in a combined approach. Calculations in this tool are performed offline and the computational time is in the order of seconds, what is multiple shorter than comparable finite element method simulations. Experimental results have been obtained allowing a direct correlation between the shape of the pressure curve and the temperature evolution and the length of the fully solidified (and thus compressed) part in the rolling gap zone (deformation length – LD), which directly correlates with the effective total equivalent stress. By using the sensor and layer model, it is possible to adapt a digital twin that can be used for on-line estimation of the final strip parameters obtained in the TRC process.

KEYWORDS: TWIN ROLL CASTING, ROLLING, LAYER MODEL, DIGITAL TWIN, SENSOR

INTRODUCTION

The aim of the research was to create a digital twin that will operate online in real time during the TRC trial, by using data from the rolling plant measurement system together with data from a combined pressure and temperature sensor in the rolling gap. In this way it will be able to calculate in a very short time the final parameters of the currently rolled strip, allowing manual control of the process to achieve the desired microstructure. So far, in this work an offline digital twin has been developed and an innovative sensor concept for pressure and temperature measurement in the rolling gap has been implemented and adjusted.

So far, the experimental study with pressure and

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temperature sensor has been carried out on the wrought alloy Mg AZ31 (1-3). In addition, first trials have been carried out with ZAX210 (4) alloy at IMF to further extend the study to other magnesium alloys at a later stage. As a solidification start point is not yet measurable, the solid part and thus the forming length of rolling gap can be identified, which can be further aided by a digital twin.

Due to the nature of the TRC, current control of the processes occurring in the rolling gap is difficult due to bad physical accessibility and due to the high temperatures. For this purpose, a sensor concept consisting of a pressure sensor and two thermocouples placed under the surface of the roller was developed. It provides data on the temperature distribution changes in the roller at different rotational speeds and on pressure variation with the selected parameters. The data from the sensor and the TRC plant measurement system were used as input parameters for the digital twin, which is the layered model presented by Schmidtchen, extended with a viscous layer [6]. When the measured and calculated results were compared, they were found to be similar, confirming the effectiveness of the layered model.

SENSOR USED IN RESEARCH

An important part of the initial research was to develop a sensor concept that can operate at high temperatures, up to approx. 600 °C. finally, it was decided on a sensor with a piezoelectric layer (5), which can be mounted in very small mounting space and is suitable for incorporation into a roller surface. As this sensor is only able to measure pressure, so it was also decided to put two thermocouples in one measuring line, measuring temperature at two different heights.

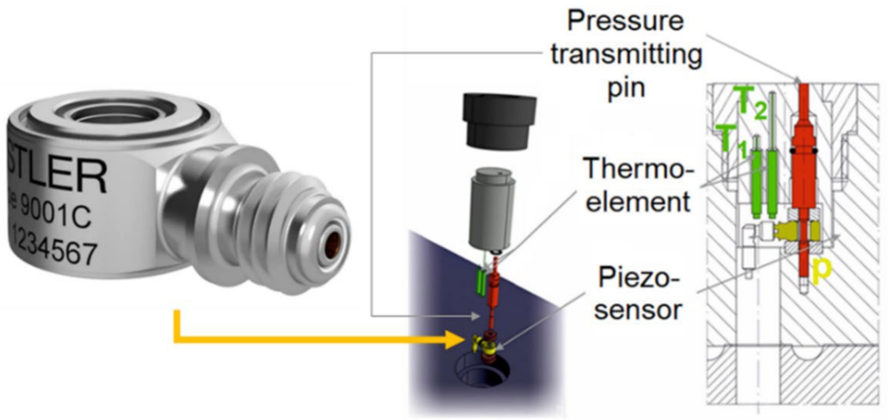

Fig.1 - Concept of the combined pressure and temperature sensor .

As presented in figure 1, Kistler 9001C sensor was used for pressure measurement, which measures forces in the Z direction. Unfortunately, the use of long sensor wires was unavoidable for this measurement system. If a small amount of charge is applied to the sensor through a long wire with sufficient capacity and insulation resistance, the measurement signal at the end of the wire will be very low, so an additional signal amplifier was installed. However, the biggest advantage of this sensor is that it can be placed under rough conditions. Signal wires were routed through an additional cooling channel inside the roller. The pin (red in Figure 1) is guided to the surface of the roller and measures the pressure over a small area. In addition, two thermocouples placed at different heights (green in Figure 1) were mounted to observe the heat flow in the roller surface. In order to mount the whole sensor, a hole was drilled from the outside, which connects to the cooling channels. Sensor signals are detected on the roller and transmitted wirelessly to the system. In the rotating roller, energy is supplied by a battery that allows for 12 hours of operation.

ANALYSIS OF THE RESULTS OF THE TRC PROCESS AND THE DIGITAL TWIN

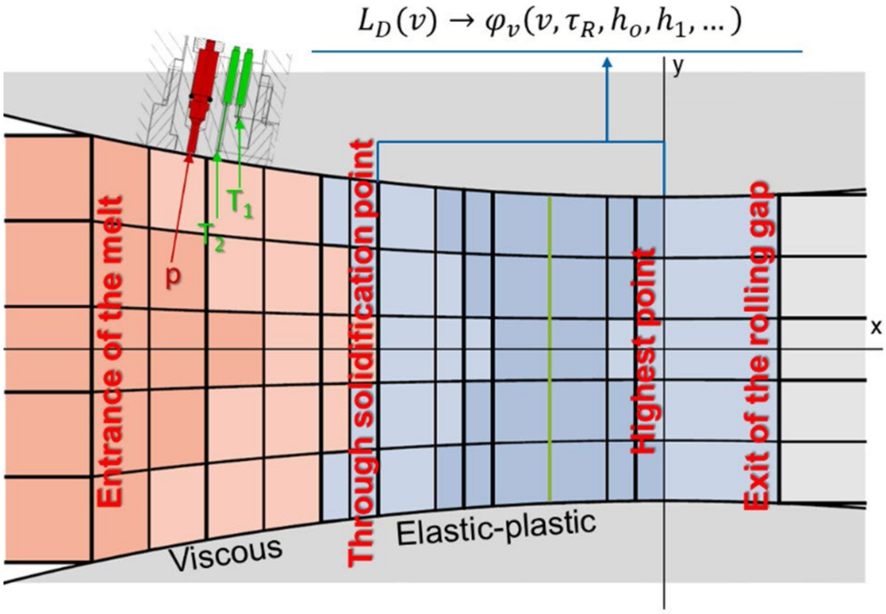

Fig.2 - Schematic representation of the adapted layer model considering viscous-to-solid transition.

The most important recent development of Layer Model is the extension of the classical elementary elastic-plastic theory to the viscous model (6-7). Two main regions can be distinguished (Figure 2 left side): the red region is the viscous region where the material is melted and formed as a viscous fluid according to Newton's law. Different shades of red indicate the viscous states – from dark to light they are liquid and mushy, while the blue part is the fully solidified, elastic-plastic model. In the layered model of the TRC process, the material is divided into individual layers parallel to the rolling direction, which are subject to local solidification conditions, strength development, and solid deformation. The partial approach consists of a viscoplastic design core for the liquid and mushy region and an isotropic-elastic-plastic design core for the solidified region. The solution is the same as in classical elementary theory, except that models are created individually for each layer.

Due to the complexity of the problem, most simulations currently used for this purpose are based on the finite element method. However, the finite element method, compared to the layer model, requires too much computational time to generate larger variants of data, especially for nonlinear problems, due to the large number of iterations. For highly nonlinear problems, the computation time of FE calculations range from several hours to several days, which definitely prevents the FEM from being a fast digital twin. The Freiberger layer model, on the other hand, requires an order of magnitude less computational time for conventional rolling processes by taking approx. 300 seconds when computing for five layers. The most important input parameters for the layer model include the number of layers, liquid metal temperature, rolling gap height, roll radius, roll speed, and roll temperature. Within the current model formulation, all these data are kept constant. In addition, parameters such as friction values, initial material deformation, and fluid pressure must be determined. The material data of the AZ31 material was used as the thermo-mechanical properties. With these inputs, the layered model can provide data such as the deformation length (L_D), but also temperature and pressure distribution as well as rolling force and torque.

ANALYSIS OF THE RESULTS OF THE TRC PROCESS AND THE DIGITAL TWIN

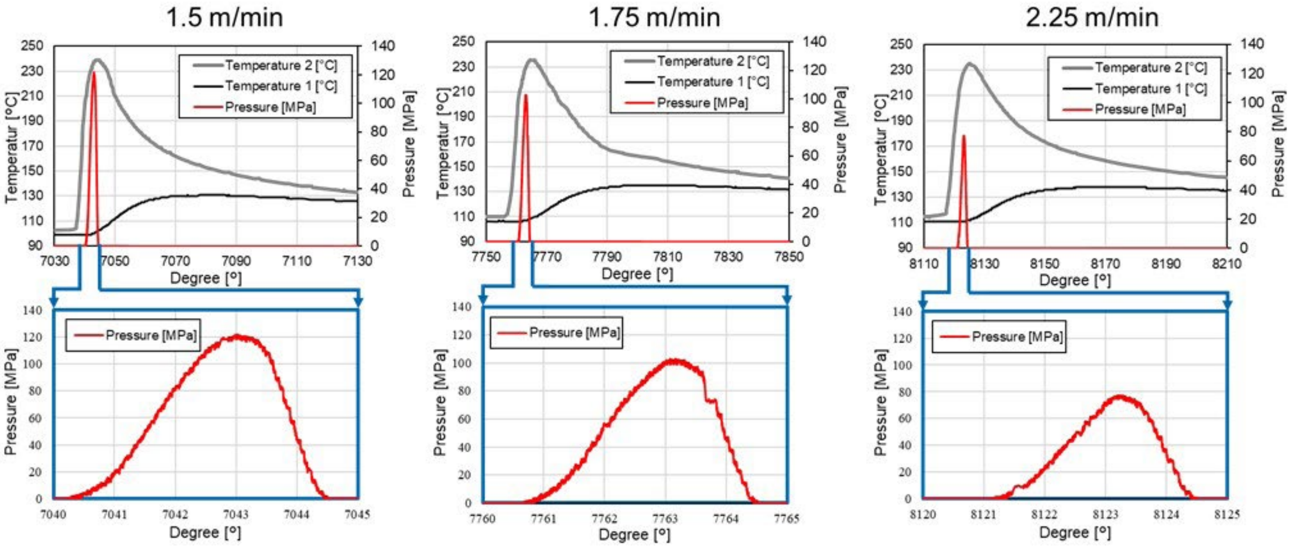

Fig.3 - Results for temperature and pressure in the rolling gap at different TRC speed (1,5, 1,75, 2,25 m/min).

Figure 3 shows the results for the piezosensor and the two thermocouples for the entire length in the rolling direction for three exemplarily TRC speeds. It can be seen that with increasing TRC speed the temperature measurements close to the roll surface (Temperature 2) and for the pressure decrease. This is due to the fact that at higher TRC speeds the solidification front moves towards the exit of the rolling gap, so that the deformation time and thus the deformation length L_D is lower. In contrast, the thermocouple further away from the roll surface recorded higher temperatures as the TRC speed increased, due to the interior of the roll was getting hotter because of less time in between two material contacts.

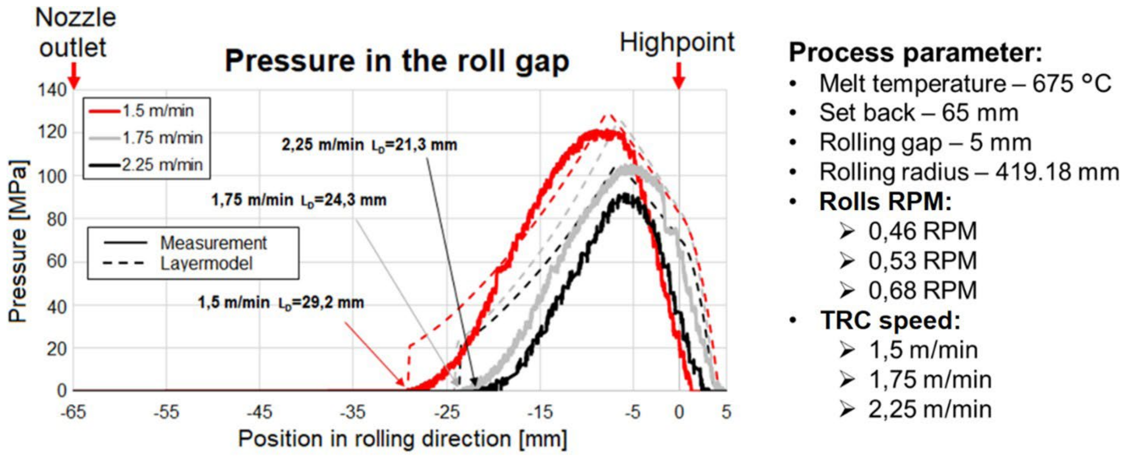

Fig.4 - Comparison of results from the layer model and the pressure sensor.

Figure 4 shows the results for pressure obtained from the layered model using only the mentioned initial parameters compared with measured data. It can be seen that the pressure spike starts immediately, it is due to the fact that once the liquid is in contact with the roller surface, rapid heat transfer occurs and the liquid is cooled to a temperature where plastic deformation is possible. At higher rotational speed and thus increasing TRC speed, the fluid is transported a greater distance into the gap before it reaches a temperature sufficient to solidify and to initiate deformation. As the liquid temperature decreases, the L_D increases, causing the solidification front to move toward the nozzle. It is shown that the shift of the solidification front can be observed by measuring the pressure near the roller surface. Additionally, this confirms that the layered model as well as the new combined sensor yield reasonable results.

TENSILE STRENGTH AND GRAIN SIZE

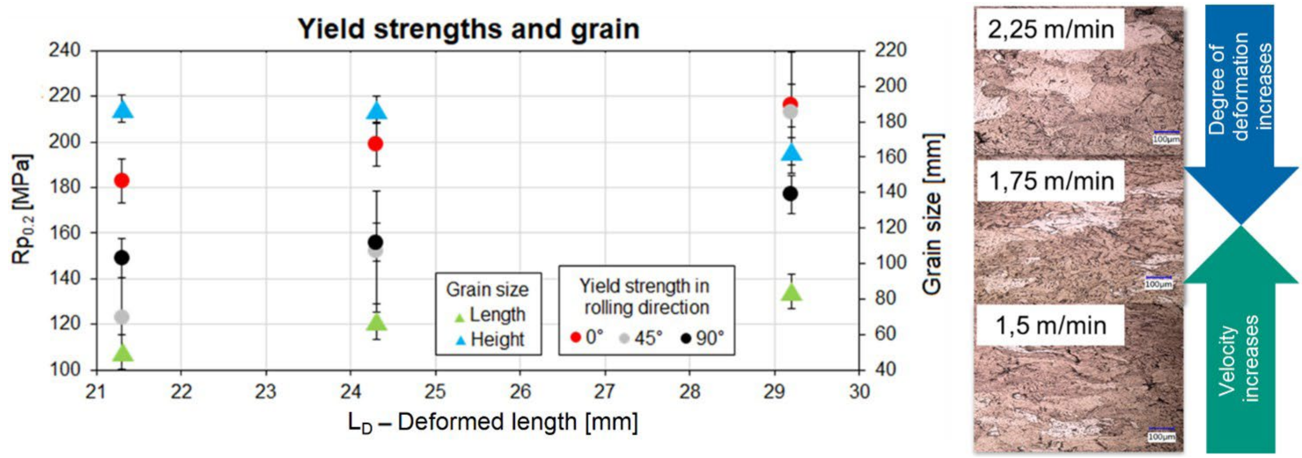

Fig.5 - Dependence of average grain size and tensile strength as a function of L_D.

For all three rolling velocities, microstructure observations and tensile tests were carried out in three directions relative to the rolling direction (0, 45 and 90 °). Grain height and length were also measured as part of the microscopic analysis. Figure 5 shows the relationship between tensile strength and average grain size in length and height as a function of L_D. It can be seen that the grains increasingly deform as the TRC speed decreases, which correlates with the stress increase inversely proportional to the TRC speed. In addition, texture studies have shown that AZ31 exhibits an increasing basic texture with decreasing TRC speed, which is a result of the forming conditions with an increase in deformation length and which is undesirable at further stages of forming.
Depending on the degree of solidification, the maximum deformation length can be obtained at a TRC speed of 1.5 m/min. At high speeds, at the highest point of the rolling gap, the core material is still liquid and its solidification structure resembles that of the casting process, so dendritic structures are much more common.
Looking at the results of the tensile test, it can be seen that the highest material strengths were obtained at a speed of 1.5 m/min, for 0° orientation in the rolling direction. This can be seen when comparing it to the results for 90°, where the yield strength is lower.

CONCLUSION

A successful TRC process using a sensor to record pressure and temperature in the rolling gap, aided by an offline digital twin in the form of a layered model, allowed for a deeper understanding of the mechanisms occurring during the process and in the material itself. The results obtained from the sensor were compared with the values measured by the rolling plant measurement system. It was found that the pressure varies in proportion to the torque and rolling force and inversely proportional to the linear TRC speed, which agrees with the reasonable process relationships. In parallel, a simulation was performed using the data collected by the measurement system as input parameters. By analyzing the results, it was confirmed that the starting point of the deformation length L_D moves towards the nozzle as the rolling velocities decreases. On the other hand, as L_D increases, the pressure in the rolling gap increases because the deformation starts earlier. This is caused by the distance at which the first contact between the liquid and the roll surface occurs, as well as by the exposure time of the rolls to the cooling system and the environment. The sample obtained at 1.5 m/min showed the best properties.

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