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CONCEPT OF THERMAL MODELLING FOR HOT STRIP ROLLING OF MAGNESIUM

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Abstract

The paper introduces a concept for the reversing hot rolling of magnesium strip consisting of reheating of twin roll casted rough strip, carrying of coil from a furnace to coiler, setting down on mandrel, uncoiling, hot rolling and coiling of the magnesium strip. In the first stage the thermal models should be established. These models shall serve in the subsequent stages in order to support by developing of a roll gap model as well as model for forecasting the microstructure and material properties of the magnesium strip. Moreover, the paper represents the state of the concept development of the thermal models. Up to now, the following technological steps are implemented: reheating of the coil, transport of coil from furnace to the coiler, setting down on the mandrel and uncoiling of coil. The modelling of these models is worked out in three dimensions and are calculated numerically by using the Finite Element Method.

Key words: hot strip magnesium rolling, heating, numerical modelling

1. INTRODUCTION

The application of magnesium alloys becomes more important in various industrial fields over the past years. This is due to the fact, that magnesium alloys have high functional properties by contrast with the most frequent applicable materials as steel and aluminum. Magnesium stands out by means of its low density (1740 kg/m^3), which is 35% lighter than aluminum and 78% lighter than steel. The production of semi-finished products from magnesium alloys is usually carried out at higher temperatures. It causes through its hexagonal lattice structure (Kawalla et al., 2006). In this paper the technological chain of magnesium strip production at the institute of metal forming, TU-Freiberg is considered. The details of the technological chain will be considered subsequently in this paper. Moreover, this paper introduces a modelling concept for reversing hot strip rolling of magnesium alloy AZ31. We present the current state of this project. In the last section we show the results of simulation.

2. TECHNOLOGICAL CHAIN FOR HOT STRIP ROLLING OF MAGNESIUM ALLOY AZ31

The Institute of Metal Forming have been carrying out the research on the production of industrially applied strip/sheet from magnesium alloys since 2002. Since then, it has been achieved substantial progress in the developed technology. Therefore, the current technological route can be subdivided into 3 steps:

1. Twin-Roll (TR) casting (manufacturing of rough TR casted strip or TR casted coil)

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2. reheating of TR casted coil (getting of rolling temperature)
3. reversing hot strip rolling up to appropriate thickness

Figure 1 shows the whole technological chain at the Institute of Metal Forming.

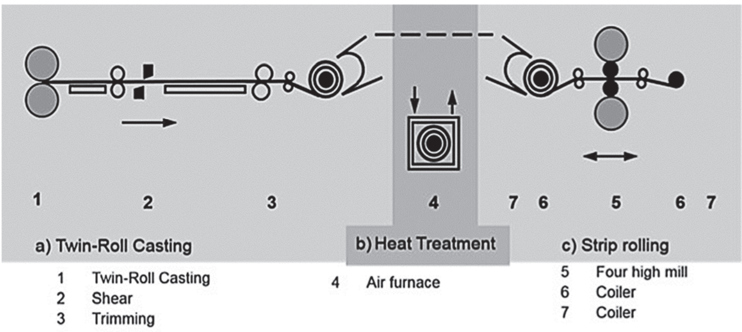

Fig. 1. *Technological chain for hot strip rolling of magnesium alloys.*

3. THERMAL MODELLING CONCEPT

The thermal modelling concept for hot strip rolling of magnesium alloys consists of technological steps starting from reheating of TR casted coil up to manufacturing of semi-finished products through hot reversing rolling. Therefore, the reversing hot rolling step of magnesium alloy AZ31 can be subdivided in following sub-steps:

1. reheating of Twin-Roll casted coil in furnace,
2. transport of reheated TR casted coil from furnace to coiler of reversing four-high mill,
3. putting of coil on the mandrel of the coiler,
4. unrolling of coil,
5. reversing hot strip rolling (roll gap),
6. roll-up of coil.

Every sub-step is modelled individually separated from each other. However, the results of single sub-steps are connected with each other. Moreover, a coil-model was modelled, which is used within modelling. The description of coil-model and single steps will be further given. The current state of work are the sub-steps including a coil unrolling, which are being describing subsequently in this paper. This issue, i.e. the modelling of coil unrolling, which can be found in the bibliography, has been treated in a number of different ways by various authors (Troyani, 1996; Troyani & Montano, 1999). In all these works the solution was achieved using geometrically adaptive finite element in 2D, 8-node isoparametric elements to adapt the curve shape changing of elements. In our case we have used a different approach to deal with this aspect of the problem. We perform the modelling of coil unrolling on the one hand in 3D and in other hand we execute the geometrical modelling of coil unrolling and the calculation of heat transfer sequentially. The details of implementation will be given below.

3.1. Governing equations

The transient heat transfer calculations are based on the convective-diffusion equation (Ozisik, 1993)

$$c_p\rho\frac{\partial T}{\partial t} = \nabla^T k\nabla T \tag{1}$$

where $T(K)$ is temperature, the matrix $k = \{k_{i,j}\}_{ij} = 1;\ldots;3$ (W/(m K)) contains the thermal conductivity according to the spatial directions, ρ (kg/m^3) is the density, and c_p is the specific heat capacity. The solution of equation (1) has to satisfy the boundary conditions given below. In the present model, Neumann's type of boundary conditions are used for coil heating/cooling. Moreover, the surface of the hollow cylinder is divided into single segments Γ_n, whereby the boundary conditions distinguish from boundary segment to boundary segment. We have

1. the inner mantle surface Γ_1,
2. the outer mantle and the top of the hollow cylinder Γ_2, and
3. the bottom of the hollow cylinder (symmetry) Γ_3.

The boundary conditions related to these segments are

$$\vec{n}\cdot(k\nabla T) = -h_1(T - T_{\Gamma_1}) \text{ on } \Gamma_1, \tag{2}$$

$$\vec{n}\cdot(k\nabla T) = -h_2(T - T_{\Gamma_2}) \text{ on } \Gamma_2, \tag{3}$$

$$\vec{n}\cdot(k\nabla T) = 0) \text{ on } \Gamma_3, \tag{4}$$

where $T_{\Gamma n}$ is the temperature of the air into furnace, and hence of the coils boundary; h_k, $k = \{1, 2\}$ is the heat transfer coefficient and $\vec{n}$ is the outer normal to the boundary surface. A radiative heat transfer boundary condition is not considered in the present development. The initial temperature is given by $T(t_0) = T_{start}$ in the beginning of calculation.

The idea of the finite element method (FEM) is to bring equation (1) into the variational or weak from by multiplying equation (1) with a test function $v \in V$, where V is the space of test function, e.g. $v \in C^1(\Omega)$. The weak form of a differential equation is a weight-integral statement that is equivalent to both the governing differential equation as well as certain types of boundary conditions. We obtain the variational equation

$$\int_\Omega \rho c_p \frac{\partial T(t,x)}{\partial t} v(x)dx = \int_\Omega \nabla^T k(T(t,x))\nabla T(t,x)v(x)dx \qquad (5)$$

for all $v \in V$.

After applying Green's formula to equation (5) and inserting the boundary conditions we obtain

$$\int_\Omega \rho c_p \frac{\partial T(t,x)}{\partial t} v(x)dx = -\int_\Gamma h_1(T(t,x)-T_{\Gamma_1}(t))v(x)ds - \int_{\Gamma_2} h_2(T(t,x)-T_{\Gamma_2}(t))vds - \int_\Omega k(T(t,x)\nabla T(t,x)\nabla v(x)dx, \qquad (6)$$

where the integral over the symmetry boundary Γ_3 disappears. After discretization of the domain Ω, the boundary Γ, and of all functions by finite elements, we finally obtain the discrete problem

$$D\frac{\partial T}{\partial t} + (K(T)+H)T = G, \qquad (7)$$

where K is stiffness matrix, D is the mass matrix, and the matrix $H = H_1 + H_2$ corresponds to the functions h_k, $k = \{1, 2\}$ and $G = G_1 + G_2$ is the vector corresponding to the given data $T_{\Gamma k}$, $k = \{1, 2\}$, in the boundary integrals. By the dependence of the stiffness matrix from the temperature this is a nonlinear problem. For the details of the used FEM approach we refer to Section 2 in (Prüfert, 2014).

3.2. Modeling of the coil

The domain $\Omega \subset R^3$ is modelled as a hollow cylinder with inner radius r_{inner}, outer radius r_{out} and width d. We assume the magnesium coil as a continuum and model the layer structure by using a non-isotropic formulation in the equation. In contrast to most former works, we consider the heat transfer problem in Cartesian coordinates instead of the more usual cylindrical coordinates. The reason for solving this problem in Cartesian coordinates is the further simulation of the whole magnesium hot strip rolling process. The rolling process of strip will be considered by modelling in connection with uncoiling/coiling process in Cartesian coordinates. Thereby, the transformation from cylindrical to Cartesian coordinates should not be executed. The developed coil model have been modelled with the dimensions 1.0 m (outer diameter) x 0.3 m (inner diameter) x 0.6 m (width of strip) and 0,005 m (thickness of strip). In figure 2 is shown the generated mesh for the modelled coil geometry. The mesh was so generated that the mesh on the outer and inner side of the coil is fine while at intermediate location is spaced out evenly. The shown coil geometry in figure 2 was meshed through 59300 prism elements with 36210 nodes.

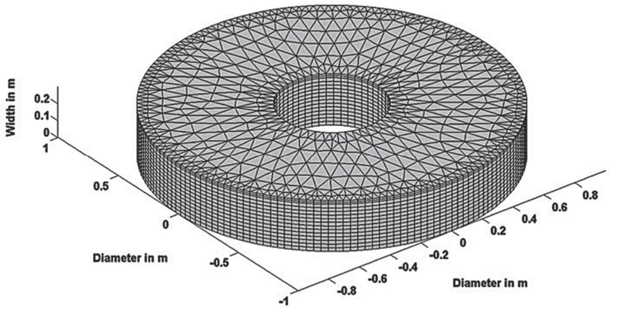

Fig. 2. *The modelled and meshed geometry of coil model.*

3.3. Reheating of the coil in furnace

The reheating of coil occurs in the special for magnesium engineered air circulation furnace. The principal of heating process in the furnace is based on the circulation of the heated air within a chamber by means of furnace's fans. Thereby, the temperature distribution in the furnace chamber is set during heating process homogeneous. However, a separated furnace model has not been developed for calculation of furnace temperature. It is assumed therefore the uniform changing of the furnace temperature in the whole chamber during heating.

In order to calculate temperature state of furnace it was measured the temperature within the furnace chamber by means of thermocouple during coil reheating. Therefore, based on the obtained experimental data were correlated the essential thermal coefficient such as heat transfer and thermal conductivity inside in a coil due to inverse method (Beck et al., 1996). Hence the calculation of temperature state of the furnace is carried out based on an intended heat transfer coefficient

$$h = 1.2 \cdot e^{3.285 + 1.57 \cdot 10^{-3} T} \qquad (8)$$

It is also assumed that the variation of coil temperature during coil heating/cooling occurs by means of a calculated thermal conductivity inside into coil without consideration of exogenous effects/factors:

$$k_{rad} = 19.72 \cdot \left(1 - e^{-\left(\frac{T}{131.79}\right)^{0.89}} \right) \tag{9}$$

These values have been already introduced in (Nam et al., 2014).

3.4. Cooling of the coil

The coil is being transported from the furnace to the coiler as soon as the coil reheating is completed. During the coil transport occurs small losses of temperature due to free convection. The room temperature is assumed as 25°C. The coil is subsequently is being put on the mandrel. It leads to the next heat losses due to contact with the mandrel. However, the mandrel consists of a outer insulation layer and steel. Thereby the heat losses are minimal. Furthermore, the thermal conductivity of mandrel is assumed as 10 times smaller than thermal conductivity of steel.

3.5. Unrolling of the coil

As soon as the coil has been put on the mandrel, the coil unrolling is occurring. This unroll process is modeled in the way that geometrical modelling of coil unrolling and the calculation of heat transfer take place sequentially, but will be performed for every time step. By decreasing the time increment, this process will converge to the continuous simultaneous cooling when unrolling process. Since we consider the coil as a continuum, we define the unrolled coil as union of a hollow cylinder and a thin sheet, where the diameter of the cylinder decreases if the length of the sheet increases. Here, the main difficulty is the transport of the temperature distribution to the next grid. We do this by layer-wise rotation, shrinking of the grid in radial direction and linear interpolation of the data, cf. figure 3.

4. IMPLEMENTATION

The implementation of the model has been carried out in MATLAB® by using the object-oriented FEM Toolbox OOPDE (Prüfert, 2014). The geometry of the coil is a generalized cylinder. By this fact, we can model it by three dimensional prism elements, where we also can use the symmetry of the coil with respect to the $x-y$- plane. The software is modularized, i.e. for every step in the technological chain there is a separated class. These classes are derived from an abstract super-class that implements all common properties and methods, cf. figure 4.

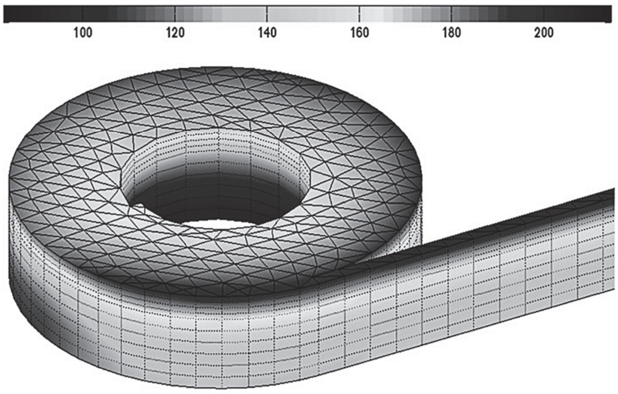

Fig. 3. Unrolling (without solving the heat transport equation) of approximately 4 meter of the coil after 1 hour heating. The first cool inner layer of the coil becomes visible. To make the effect visible we use here a sheet thickness of (unrealistic) 0.05 meter.

The classes `coilHeating` and `coilCoolingOnDorn` differ in the boundary conditions and the source term, while `coilCoolingOnDorn` and `coilUnrolling` differ in the geometry, i.e. in the grid property.

The unrolling method of `coilUnrolling` class manages the transformation of the 3D grid as well as the transport of the solution from grid to grid. In every time step of the transient heat transfer calculation one unrolling step will be performed.

Note that the transformation of the grid makes it necessary to re-assemble the linear system. From that reason we can also update the nonlinear temper-

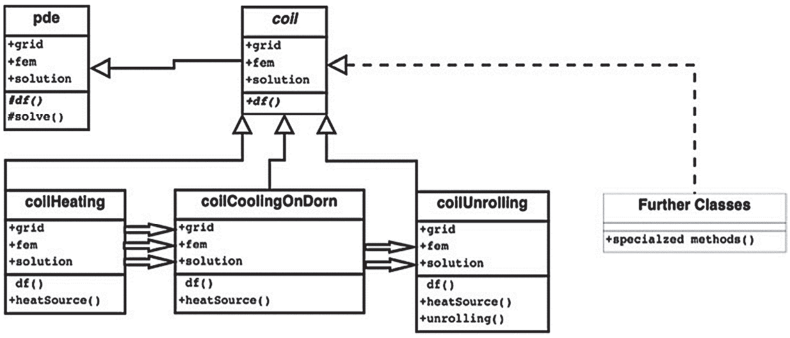

Fig. 4. Class diagram of coil classes. The lower row are implement the technological chain while the upper row are abstract classes implement the mathematical basis methods as e.g. non-linear solvers, time integrators etc. The arrows symbolize the data transport between the objects of the classes in the technological chain.

ature diffusion coefficient without any additional effort in every iteration step. This is in contrast to the adaptive update strategy for the coil heating procedure suggested in (Nam et al., 2014), where the adaptive update of the coefficients speeds up the computations. A further problem is caused by the fact, that for every step within the rolling process we have a solution on a changing grid, i.e. we should store the solution and the associated grid. This results in an enormous growing of the data within the memory while running the simulation. However, since a call of the `unrolling` method is rather cheap we do not store the grids and only the solutions at given checkpoints and the information about the length of the sheet. The associated grid will be recompute from this information if needed. The main advantage of this approach is that we can add very easily further modules as for example a module for the strip rolling, re-heating and so on. These modules will be derived from coil class and only specialized method for e.g. strip rolling must be added, cf. figure 4.

5. RESULTS

The temperature distribution in the coil was calculated in every technological step. The temperature of previous step was used as an initial temperature for the following step. The heating of coil occurred according to a reheating furnace program, which is shown in figure 5.

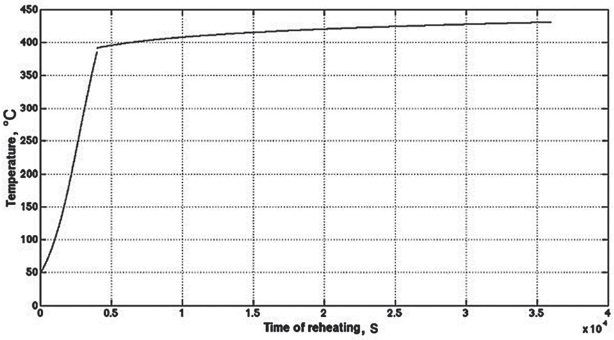

Fig. 5. Calculated furnace program for magnesium coil reheating.

The total duration of reheating the coil was approximately 10 hours. The temperature distribution within the coil cross-section is shown in figure 6. Based on the results it could be noted that the temperature difference is lesser than 5°C. Hence, the temperature of coil is therefore distributed homogeneously. At the same time the temperature distribution reveals correct behavior form a physical perspective. The quantitative verification of results of coil reheating has been reported in (Nam et al., 2014).

The following figures show the temperature distribution within the coil cross-section at reheating and transport steps. The transport step usually occurs very fast due to loss temperature and takes about 1-2 minutes. The coil is being cooled down due to effects of free convection, cf. figure 7. For lack of specific experimental data pertaining to the present application, the value of 13 W/m^{2}K for the free convection was used (Meyer, 2005).

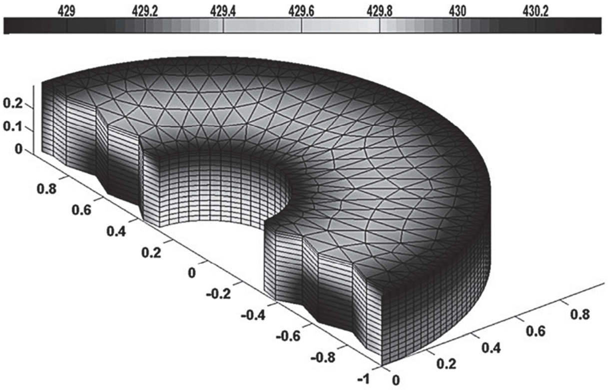

Fig. 6. Temperature distribution within the coil crosssection after reheating.

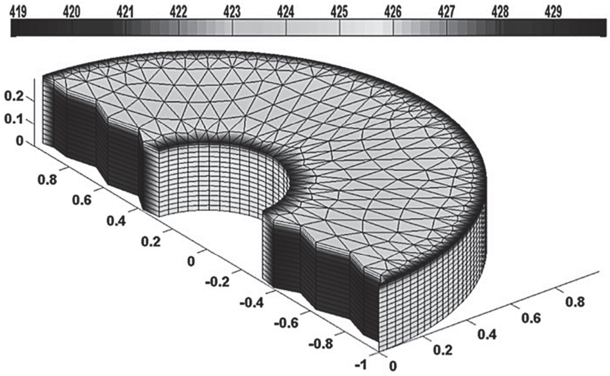

Fig. 7. Temperature distribution within the coil crosssection after transport to the coiler.

The development of the temperature during unrolling of the coil is shown in the following figures 8-11. We have simulated 10 seconds of the unrolling process, where a magnesium strip of approximately 1.6 meters was unrolled. The temperature lost at the edges of the strip is visible. Within this time the unrolled strip reaches the guide pulley of reversing four-high mill. It may be also noted that convective heat loss of strip during coil unrolling before the guide pulley does not exceed on an average 10-20°C.

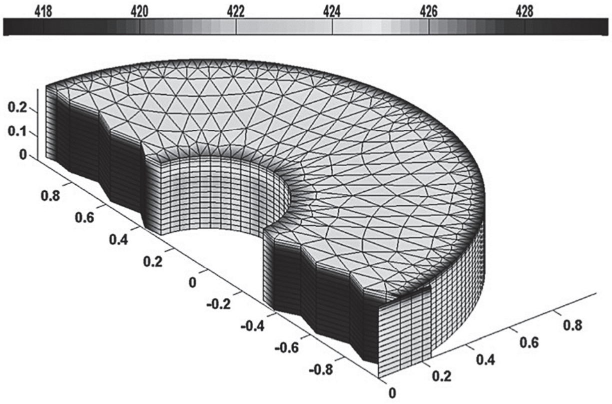

Fig. 8. Temperature distribution after 1.5 s.

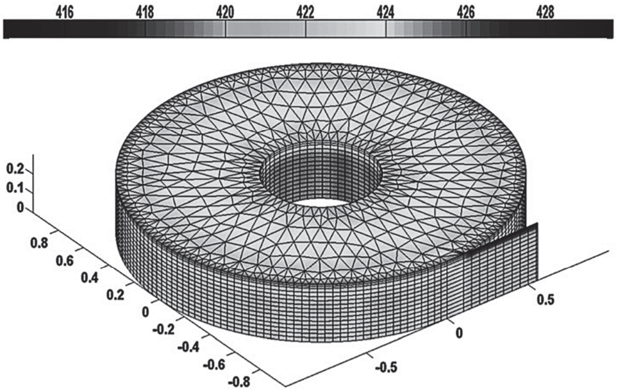

Fig. 9. Temperature distribution after 3.5 s.

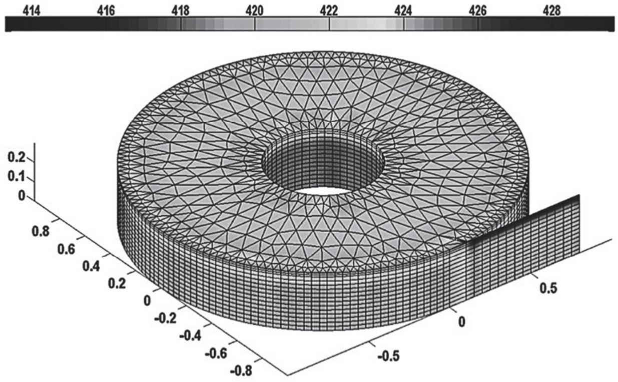

Fig. 10. Temperature distribution after 5 s.

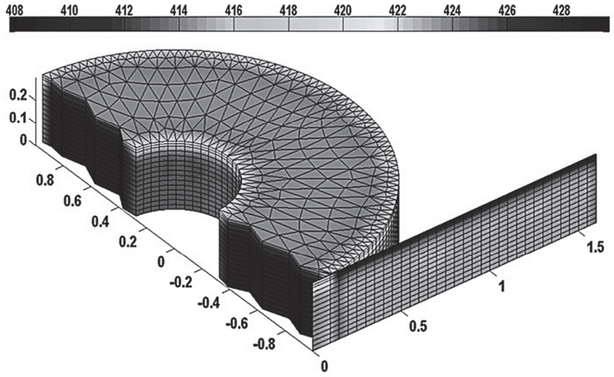

Fig. 11. Temperature distribution after 10 s.

In the near future the experimental test will be carried out the measurements of temperature distribution in the unrolled strip during unrolling process in order to verify the simulation results.

6. SUMMARY

A modelling concept for reversing hot strip rolling of magnesium alloy AZ31 was introduced in this paper. Moreover, it was presented the state of work. A worked out mathematical 3D model is developed to access the temperature state during technological steps as reheating, transport and unrolling of coil. This model considers the heat transfer effects due to a heat conductivity and convection. Besides it was proposed the new modelling approach to modelling of unrolling process. It was solved a geometrical modelling of unrolling process in connection with solving of heat transfer problem. By the solving of heat transfer problem was considered the unrolled strip as well as changed thereby volume of coil in interaction with each other. Finally, it was shown the numerical results for 5 mm thick, 600 mm width strip of magnesium alloy AZ31 after reheating, transport from the furnace to the coiler and during the uncoiling process.

In the near future the experimental tests will be performed to verify the predictions of simulation results.

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KONCEPCJA MODELOWANIA ZJAWISK CIEPLNYCH ZACHODZĄCYCH PODCZAS WALCOWANIA NA GORĄCO BLACH Z MAGNEZU

Streszczenie

W pracy przedstawiono koncepcję technologii nawrotnego walcowania na gorąco blach z magnezu, składającą się z podgrzewanych dwóch walców do odlewania ciągłego materiału wsadowego, transportu zwoju z pieca do zwijarki, odłożenia materiału na trzpień walcowniczy, rozwijania, walcowania na gorąco i zwijania blach. Na wstępie opracowane zostały modele termiczne. Modele te odzwierciedlają zjawiska zachodzące w kolejnych etapach procesu, jak również uwzględniają model szczeliny walcowniczej oraz model rozwoju mikrostruktury i własności materiałowych blachy. W pracy zaprezentowano dotychczasowy stan prac związanych z opracowywanymi modelami termicznymi. Jak dotąd, zostały zaimplementowane następujące etapy technologiczne: podgrzewanie zwoju, transport z pieca do zwijarki, ułożenie na trzpieniu walcowniczym i rozwijanie zwoju. Dla wymienionych zagadnień opracowano rozwiązania w trzech wymiarach i przeprowadzono obliczenia numeryczne z użyciem metody elementów skończonych.

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