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NUMERICAL MODELING OF MACROSEGREGATION AND STRESS-STRAIN STATE DISTRIBUTION IN SLAB DURING CONTINUE CASTING WITH SOFT REDUCTION

NUMERYCZNE MODELOWANIE MAKROSEGREGACJI, STANU NAPRĘŻEŃ I ODKSZTAŁCEŃ WE WLEWKU PŁASKIM ODLEWANYM W SPOSÓB CIĄGŁY Z UWZGLĘDNIENIEM PROCESU SOFT REDUCTION

The center segregation is forming in the slab during continuous casting process. The segregation of elements in the slab is negative influences on mechanical, chemical and microstructure of final product. One of the methods of decrease the center segregation is mechanical soft reduction process. The efficiency of soft reduction is dependent on value and localization of soft reduction and parameters of continuous casting process. Moreover, the soft reduction process to change the stress-strain state in the slab and it can cause formation cracks on slab surface. The purpose of this paper is to develop a numerical FEM model of continuous casting process with soft reduction process and optimization of parameters of soft reduction for industrial example. The proposed numerical model of slabs casting with soft reduction technology takes into ac-count the processes of crystallization, thermal stress, diffusion, macrosegregation and mechanical deformation.
Keywords: continuous casting process, macrosegregation, mechanical soft reduction, numerical modeling

W procesie krzepnięcia wlewków odlewanych w sposób ciągły zachodzi zjawisko segregacji pierwiastków. Zjawisko to powoduje powstawanie niejednorodnej struktury we wlewku co niekorzystnie wpływa na własności mechaniczne chemiczne i mikrostrukturalne wyrobów finalnych. Jedną z metod obniżenia segregacji we wlewkach ciągłych jest zastosowanie odkształcenie wlewka w stanie półciekłym w końcowym etapie odlewania. Efektywność tej metody zależy od momentu i wielkości przyłożenia odkształcenia, prędkości odlewania czy składu chemicznego odlewanej stali. Ponad to, zadany gniot zmienia stan naprężenia i odkształcenia we wlewku co może prowadzić do powstawania pęknięć na powierzchni wlewka. W pracy przedstawiono model numeryczny procesu ciągłego odlewania stali uwzględniający zjawisko krzepnięcia wlewka, segregacji pierwiastków oraz stanu odkształcenia i naprężenia w stanie półciekłym. W oparciu o opracowany model numeryczny podjęto próbę optymalizacji parametrów procesu odkształcenia w stanie półciekłym w celu zmniejszenia segregacji pierwiastków dla warunków przemysłowych. Wykonano porównanie wyników modelowania rozkładu segregacji w przekroju wlewku z danymi doświadczalnymi.

1. Introduction

Macrosegregation is one of the most severe problems encountered in continuous casting CC of steel billets and slabs. Formation and evolution of central segregation in continuously cast ingot dependent on many factors (steel chemical composition, casting speed, cooling regime, machine geometry etc.). One of the possibility of decrease of macrosegregation by deformation of billet in a semi-solid state (Mechanical Soft Reduction, MSR). In this process by applying a small thickness reduction liquid phase is squeezing in the direction opposite to the casting that cause decrease segregation elements. Research presented in papers [1-4] show that efficiency of MRS is dependents on the values reduction, contents of liquid phase in centre of ingot moreover parameters of continuous casting process. The development of the optimal parameters of the MSR process taking into consideration the industrial conditions of the CC process, is a difficult task. However, application of the computer simulations and numerical methods can be used to solve this problem.

This work presents numerical models of crystallization, macrosegregation, stress-strain state in continuously cast ingot taking into consideration of MRS process.

Base on developed model continuous casting process a series of computer simulation were performer for the industrial conditions. Computer simulation made for slab 220×1580 mm at casting speeds 17 and 20 mm/s. Numerical results has been compare with experiment results.

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2. Mathematical models description

Presented here for the main assumptions of developed a mathematical model of continuous casting process. A detailed description of the model presented in the works [5-7]. The mathematical model of the crystallization of the ingot CC is based on the effective specific heat method:

$$c_{eff}(T)\rho(T)\frac{dT}{dt} = div(\lambda(T)\, grad(T)), \quad (1)$$

where: $\rho(t)$ – metal density, t – temperature, τ – time, $\lambda(t)$ – heat conductivity coefficient, $c_{eff}(t)$ – effective specific heat:

$$\begin{aligned} c_{eff} &= c_S(T) && \text{for} \quad T < T_S, \\ c_{eff} &= c_f + L\frac{df_S}{dt} \approx c_f + \frac{L}{T_L - T_S} && \text{for} \quad T_S < T < T_L, \\ c_{eff} &= c_L && \text{for} \quad T > T_L. \end{aligned} \quad (2)$$

In order to solve the equation (1) the variational problem formulation is used. This is based on the minimization of the functional J [8]:

$$J = \int_V \frac{1}{2}\left[\lambda(t)\left(\frac{\partial t}{\partial x}\right)^2 + \lambda(t)\left(\frac{\partial t}{\partial y}\right)^2 - 2c_{eff}(t)\rho(t)\frac{dt}{d\tau}t\right]dV + \int_F \frac{\alpha}{2}(t - t_\infty)^2\, dF, \quad (3)$$

where: α – effective coefficient of heat exchange, F – area of contact metal with tool; V – volume; t_∞ – temperature of the environment.

The model for the evolution of the macrosegregation in the ingot CC was developed based on follow principles. The concentration solute in the first portion solid phase is given by the equation:

$$C_S = C_L k, \quad (4)$$

where: k – partition coefficient of the solute elements between the liquid and the solid phases.

The concentration of solute in the liquid phase is constant in next time step of the crystallization process, and can be calculated using the mass balance equation:

$$C_L = \frac{C_{0L}F - \sum_{e=1}^{N_e} f_{se}C_eF_e}{F_L}, \quad (5)$$

where: F_L – surface of the liquid phase in the cross-section of the ingot CC; F – area of the cross-section of ingot CC; f_{se} – solid phase fraction in the FE element e; C_e – concentration of the solute elements in the FE element; F_e – area of the FE element e; N_e – number of the FE elements.

Lack of the mass balance in the element is the results of the SR process. This is due to the movement of some part of the liquid metal to the upper regions. To correctly calculate the mass balance, integration of the concentration element at surface of the ingot CC cross-section has to be performed.

The backward diffusion is solved base on the Fick's principle:

$$\frac{dC}{d\tau} = div(D(t)grad(C)), \quad (6)$$

where: $D(T)$ – diffusion coefficient of the solute elements; C – concentration of the solute elements in steel in wt%.

In order to solve the equation (6) the variation problem formulation have to be used. This formulation have to fulfil the relationship (7):

$$J = \int_V \frac{1}{2}\left[D(t)\left(\frac{\partial C}{\partial x}\right)^2 + D(t)\left(\frac{\partial C}{\partial y}\right)^2 - 2C\frac{dC}{d\tau}\right]dV. \quad (7)$$

Stress-strain state model is consider a solution of a 2-dimensional task with the linear distribution of deformation in direction of the ingot CC height (along the y axis). The solution is sought from the necessary condition of the minimum of the Lagrange variational functional:

$$J = \int_V E'\Delta\varepsilon_i^2 dV + f_S\int_V K'(\Delta\varepsilon_0 - \beta\Delta t)^2\, dV + f_L\int_V p_f(\Delta\varepsilon_0 - \beta\Delta t)\, dV + f_S\int_F \sigma_i\Delta u_i dF, \quad (8)$$

where: f_L – fraction of the liquid phase, E' – the modulus of plasticity (corresponding to the Young's modulus in elasticity), β – thermal expansion coefficient; $\Delta\varepsilon_i$ – increment of the effective strain; Δt – increment of the temperature; σ_τ – friction stress on contact between rolls and ingot CC; Δu_τ – increment of the displacement in sliding direction; K' – effective compression coefficient.

If fraction of the liquid phase is one, the equation (8) can by describe in follow form:

$$J = \int_V \frac{1}{2}E'\Delta\varepsilon_i^2 dV + \int_V p_f(\Delta\varepsilon_0 - \beta\Delta t)dV. \quad (9)$$

For solid phase equation (8) is write as

$$J = \int_V \frac{1}{2}E'\Delta\varepsilon_i^2 dV + \int_V K'(\Delta\varepsilon_0 - \beta\Delta t)^2 dV + \int_F \sigma_t\Delta u_t dF. \quad (10)$$

The equation for liquid phase (9) is not including the incompressibility condition and if cross section of liquid area is change by soft reduction, the area of liquid phase is decrease according deformation distribution in ingot.

TABLE 1

Chemical composition of material in weight percent

C	Mn	Si	P	S	Cr	Ni	Cu	Al	Nb	V	Mo
0.17	1.43	0.016	0.017	0.014	0.02	0.02	0.04	0.041	0.015	0.006	0.002

3. Experimental procedure

The macrosegregation was examined for the slab cast in one of the Polish steelworks. The strand dimension in this experiment was 220×1580 mm. The caster is bent with a radius of 10.5 m. Mechanical soft reduction zone, MSR, is situated between 18.5 and 23.3 m from the top of mould. Total reduction in the reduction zone is 1.2 mm. The chemical composition of the continuous cast steel shown in Table 1. The casting speed was 20 mm/min.

After solidification of slab the samples was cut to analyze the chemical compositions. Method of cut samples show on Fig. 1. Chemical composition analysis was performed on the spectrograph. To determine the flow curve for the steel test was performed experimental tests on the machine Zwick Z250.

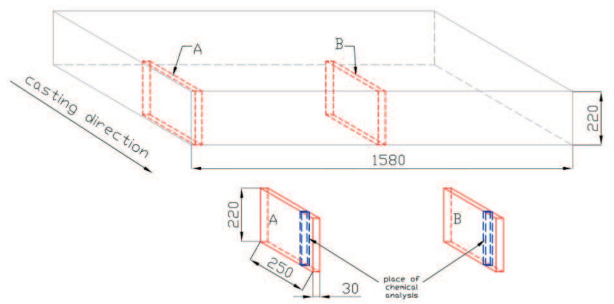

Fig. 1. Schematic illustration of sawing and analyzing of the test specimen

Base on the develop mathematical models of CC process a series of computer simulation were performer for the above industrial conditions. Thermal properties (conductivity, heat capacity, liquidus and solidus temperature) of the investigated steel have been calculated in ThermoCalc application. The diffusion coefficient and equilibrium distribution coefficient in macrosegregation model is based on the literature [9]. Computer simulations were carried out for two casting speeds: 17 mm/s (without MSR) and 20 mm/s (with MSR).

4. Results and discussion

The numerical models of continuous casting process given the opportunity solve change temperature on surface and centre of slab. On figure 2 show obtained results and mark four cooling zone in continuous casting machine. In the first zone the slab is very fast cooling in mould. Temperature on surface decrease to 870°C and this induces the beginning of the solidification process. In the following stages (zone II) the temperature increases due smaller cooling intensity (water and air cooling). In third zone the slab is cooling on air. When surface of slab is contact with rolls the temperature is jumps what can be seen on Fig. 2. Temperature in centre of slab is decrease very slow. After the solidification of slab the temperature is rapid decrease in centre. Solidification of slab is faster for the casting speed 17mm/s than 20mm/s. For casting speed 17mm/s the metallurgical length it was 18.5m and for casting speed 20mm/s it was 23.4m. Metallurgical length for industrial conditions it was 23.3m (for casting speed 20mm/s).

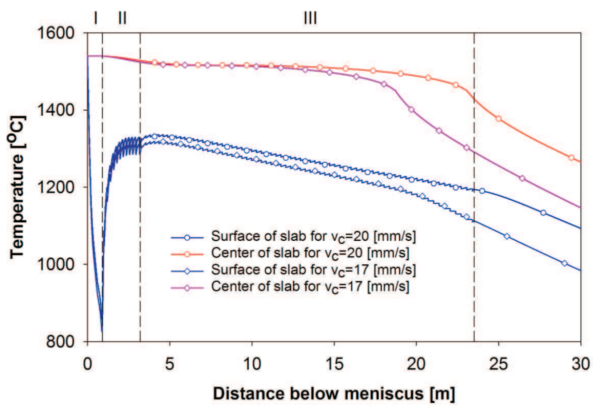

Fig. 2. Change of temperature in slab during continuous casting process

The decrease in the temperature in the mould induces beginning of the solidification process on the surface of the slab. It causes drop in the carbon concentration at the first stages of the continuous casting process. For each casting speed it was 0.069wt% (Fig. 3). In the following stages the carbon concentration increases due to the backward diffusion phenomenon. The liquid fraction is lessening in next steps of CC process and it cause increase of carbon concentration in centre of slab. Maximum carbon concentration in center line of the slab was at the moment when last fraction of liquid phase is solidification. For casting speed 17mm/s maximum carbon concentration it was 0.611wt%, for casting speed 20mm/s it was 0.505wt%. During soft reduction process liquid phase is squeezing in the direction opposite to the casting that causes decrease value of maximum carbon concentration in centre of slab Fig. 3.

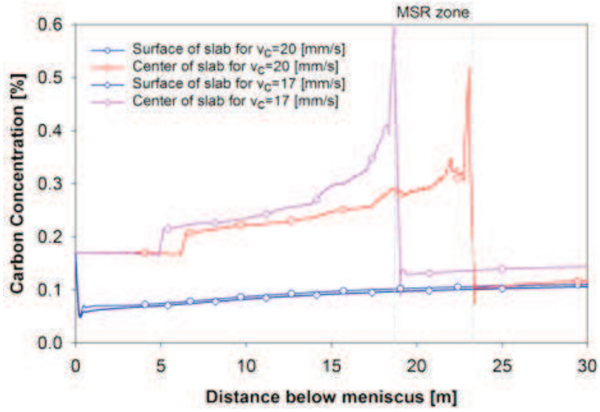

Fig. 3. Change of concentration carbon in slab during continuous casting process

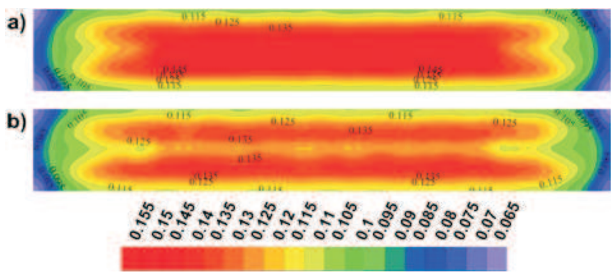

Fig. 4. Distribution of carbon concentration in the cross-section of slab; a) Vc=17mm/s; b) Vc=20mm/s

For lower casting speed slab solidification before MSR zone by which final concentration was higher in centre slab. For higher casting speed slab total reduction in MSR zone was 1.1mm. It was decrease maximum carbon concentration in centre of slab.

Numerical results of carbon segregation in slab compare with experiment results. On Fig. 4 show numerical and experimental results of carbon concentration vs distance along the width of slab.

In experiment maximum carbon concentrate for centre of slab was 0.138%, minimum 0.128%, average 0.133% (Fig. 4b). On surface of slab maximum carbon concentrate was 0.133%, minimum 0.119% and average 0.127%. Numerical results are similar to experiment results for casting speed 20mm/s. Difference average carbon concentrate between experiment and numerical results was 0.001% in centre slab, for surface slab it was 0.005%. For casting speed 18mm/s carbon concentrate is higher than experiment in centre slab.

The strain intensity in slab during continue casting is determined. The SR process influences the distribution of strain intensity (Fig. 5). Maximum strain intensity concentrates in slab corners. The increase in the strain intensity at the surface is cause by the bending and straightening processes occurring during CC. The MSR process influences on distribution of strain intensity. It is decrease of strain intensity in corners of the slab and it can by cause formation of fracture.

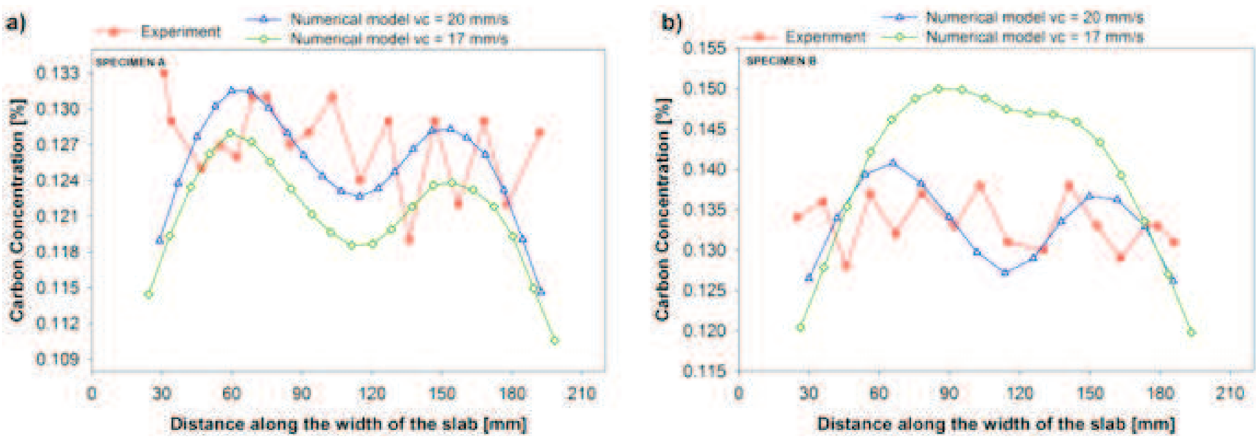

Fig. 5. Carbon concentration along the width of slab; a) centre; b) surface of slab

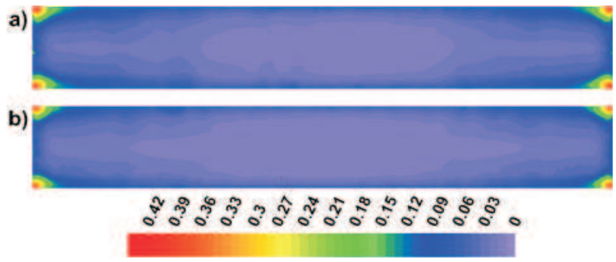

Fig. 6. Distribution of strain intensity in the cross-section in continuous cast billet, after finish of solidification process; a) Vc=17mm/s; b) Vc=20mm/s

5. Conclusion

- In this work show that base on developed numerical model of CC process can by optimization parameters of continuous casting process and MSR process.
- MSR process essentially influences on decrease of segregation in slab. The agreement between experimental data of segregation in slab and FEM calculation by elaborated model is reasonably good.
- The MSR process change the distribution of the strain intensity in slab. Maximum strain intensity concentrates in slab corners. MSR increase strain intensity and it can be cause formation of fracture.

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