THE 3D NUMERICAL MODEL OF MACROSEGREGATION IN STEEL INGOT DURING CONTINUOUS CASTING WITH SOFT REDUCTION

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Abstract

The 3D numerical model of macrosegregation distribution in continuous casting ingot was presented in this work. The numerical implementation is discussed in the context of Soft Reduction process modelling. The examples of numerical simulations of macrosegregation of carbon were showed. The influence of soft reduction on macrosegregation distribution was showed.

Key words: centre segregation, soft reduction, numerical modelling

1. INTRODUCTION

The central segregation occurs in continuously cast (CC) ingot influence on mechanical properties, chemical composition and microstructure of final products. Formation and evolution of central segregation in continuously cast ingot dependent on many factors (steel chemistry, casting speed, cooling regime, machine geometry). One of the techniques to reduce the degree of segregation is soft reduction process. 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 [1-3] show that efficiency of soft reduction dependents on the values reduction, contents of liquid phase in centre of ingot moreover parameters of continuous casting process. The development of optimal parameters of soft reduction process is difficult task. However, this problem can be solving by using numerical method and computer simulation.

The efficient numerical model of central segregation in continuously cast ingot with the soft reduction process should consist of the following components:
- model of the heat transfer and crystallization processes;
- model of the influence of constructive mechanism of the continue casting machine on metal behaviour;
- model of the segregation evolution;
- deformation model of the soft reduction process.

Some of the numerical models available in the literature are taking mentioned aspects partially into account. However there is lack of the complete model that considers all of these components. In [4-5] the mechanical and thermal models of the ingot steel with semi-solid core were presented, but without the macrosegregation model. Bellet [5] proposed termomechanical – solute transport model to be applied in mushy zones of the considered slab. That model was based on the continuum mechanics and the FEM method, and it didn't takes into account the

influence of the soft reduction process on changes in the strain-stress state.

This work presents numerical models of crystallization, macrosegregation, stress-strain state in continuously cast ingot taking into consideration of soft reduction process. Examples of computer simulation made for billet 150 × 150 mm at casting speeds 2.8 and 3.6 m/min. The results of numerical simulation segregation of carbon compared with results of experiments presented in literature [2]. Efficiency of soft reduction dependent on steel grade is presented in paper.

2. NUMERICAL MODELS

2.1. Model of crystallization

The mathematical model of the crystallization of the CC ingot is based on the effective specific heat method:

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

where: $c_{eff}(T)$ − effective specific heat, T − temperature, $\rho(T)$ − metal density, t − time $k(T)$ − heat conductivity coefficient.

Effective specific heat, which in the simplest cases is described as:

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

where: c_S − specific heat of solid phase, T_S − solidus alloy temperature, c_f − specific heat in the range of the alloy crystallization temperature, $c_f = f_S c_S + (1 - f_S)c_L$, L − hidden crystallization heat, f_S − fraction of the solid phase, T_L − liquidus alloy temperature, c_L − specific heat of the liquid phase.

In order to solve the equation (1) the variational problem formulation is used. This is based on the minimization of the functional J [6]:

$$J = \int_V \frac{1}{2}\left[k(T)\left(\frac{\partial T}{\partial x}\right)^2 + k(T)\left(\frac{\partial T}{\partial y}\right)^2 - \right.$$
$$\left. c_{eff}(T)\rho(T)\frac{TdT}{dt} \right]dV + \int_F \frac{\alpha}{2}(T - T_\infty)^2 dF, \quad (3)$$

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

2.2. Model of macrosegregation

The 3-dimensional model for the evolution of the macrosegregation in the ingot CC was developed based on follow principles. The concentration solute in the solid phase is given by the equation:

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

where: m − partition coefficient of the solute elements between the liquid and the solid phases (m = 0.3 for carbon [7]).

In the liquid phase concentration of solute assume is constant at the next time step of the crystallization process and can be calculated using the mass balance equation in cross-section of ingot:

$$C_L = \frac{C_{0L}F - \sum_{e=1}^{Ne} f_{Se}C_e F_e}{F_L}, \quad (5)$$

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.

The soft reduction process upset mass balance in centre of ingot. To correctly calculate the mass balance, integration of the concentration element at surface of the ingot CC cross-section has to be performed.

Developed model of macrosegregation takes backward diffusion into consideration in CC ingot. The backward diffusion is solved based on the Fick's principle:

$$\frac{dC}{dt} = div(D(T)grad(C)), \quad (6)$$

where: C − concentration of the solute elements in steel in wt %; $D(T)$ − diffusion coefficient of the solute elements − in the liquid phase is 10^{-7} m^2/s [8] and in the solid phase was calculated using the following relationship [9]:

$$D(T) = 0.0127\exp\left(\frac{-81301}{RT}\right). \quad (7)$$

The equation (6) is solving by variation problem formulation have to fulfil the relationship:

$$J = \int_V \frac{1}{2}\left[D(T)\left(\frac{\partial C}{\partial x}\right)^2 + D(T)\left(\frac{\partial C}{\partial y}\right)^2 - \frac{dC}{dt}\right]dV. \quad (8)$$

The principle of modelling the liquid phase squeezing to top part of ingot during soft reduction based on follow principles. The liquid phase squeezing is modelled by introduction of artificial compressibility in mechanical model of soft reduction. Let's 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:

$$J = \int_V \frac{1}{2}E'\varepsilon_i^2 dV + f_S\int_V K'\varepsilon_0^2 dV +$$

$$\cdot f_L\int_V p_f\varepsilon_0 dV + f_S\int_F \sigma_t u_t dF, \quad (9)$$

where: f_L – fraction of the liquid phase, E' – the modulus of plasticity (corresponding to the Young's modulus in elasticity), ε_i – the effective strain in stage of soft reduction; σ_τ – friction stress on contact between rolls and ingot CC; u_t – displacement in sliding direction; $K`$ – effective compression coefficient. The model of thermal stress is described in work [6,10].

If fraction of the liquid phase is one, the equation (9) can by describe in follow form:

$$J = \int_V \frac{1}{2}E'\varepsilon_i^2 dV + \int_V p_f\varepsilon_0 dV. \quad (10)$$

For solid phase equation (9) is write as

$$J = \int_V \frac{1}{2}E'\varepsilon_i^2 dV + \int_V K'\varepsilon_0^2 dV + \int_F \sigma_t u_t dF. \quad (11)$$

The equation for liquid phase (10) 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.

3. RESULT AND DISCUSSION

Base on develop mathematical models a series of computer simulation of the CC process were performed for billet 150 ×150 mm and compared with result of experiments presented in literature [2]. First variants of simulation are for casting speed 2.8 m/min, that response to 0.3 – 1.0 liquid phase in CC ingot at moment of beginning of the soft reduction process. Second variants of simulation are for casting speed 3.0 m/min, that response to 0.2 – 0.9 liquid phase in CC ingot at moment of beginning of the soft reduction process. In soft reduction CC ingot were reduced 10 mm. The chemical composition of cast steel grades is listed in table 1. Parameters of continuous casting process based on work [2].

Table 1. *Steels composition, liquidus and solidus temperatures used in model calculations.*

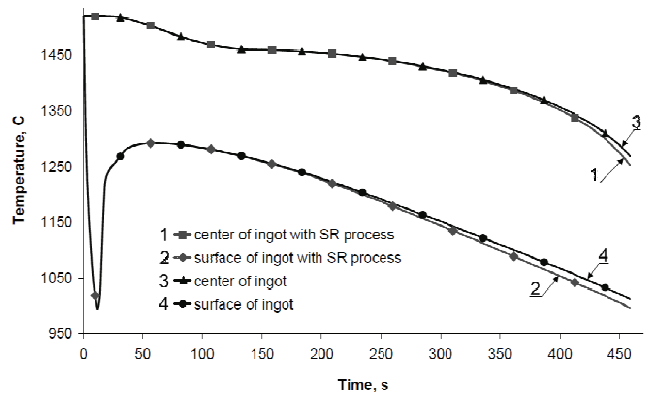| Steel grade	%C	%Si	%Mn	%P	%S	%Cr	$T_S,°C$	$T_L,°C$
C72D	0.70	0.26	0.65	0.007	0.006	0.02	1400	1490
-	0.28	0.20	1.10	0.015	0.010	0.30	1480	1530

Fig. 1. *Change of temperature during continuous casting process.*

On figure 1 presented a change of temperature during continuous casting process for casting speed 3.0 m/min. Intensive cooling in mould follows to fast temperature decrease on the surface of ingot what induces beginning of solidification process. In the following stages the temperature increases due smaller cooling intensity (water and air cooling). During soft reduction process liquid phase is squeezing in the direction opposite to the casting that causes accelerate solidification of ingot (figure 1) and influencing of change temperature.

The liquid fraction is lessening in next steps of CC process and it cause increase of carbon concentration in centre of billet. Maximum carbon concentration in center of billet was at the moment when last fraction of liquid phase is solidification (figure 2). 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 billet (figure 2). In the follow-

ing stages after solidification is occurring diffusion phenomenon that decreases carbon concentration in centre of billet. The decrease in the temperature in the mould induces beginning of the solidification process on the surface of the ingot. It causes drop in the carbon concentration at the first stages of the CC process. For variant at a casting speed of 2.8 m/min it was 0.430% and for variant at a casting speed of 3.0 m/min it was 0.390%. In the following stages the carbon concentration increases due to the backward diffusion phenomenon that increase carbon concentration.

figure 3 is showing distribution of carbon concentration at the end of CC process for all variants.

In paper [2] carbon segregation level is defined as the ratio of analyzed carbon content in core of billet C_{center} to the carbon content of the ladle analysis C_0. To compare results of numerical simulation with results of experiments [2] carbon segregation ratio was calculated in this work. Carbon segregation ratio calculated at numerical simulation including between values determined experimental and listed in table 2.
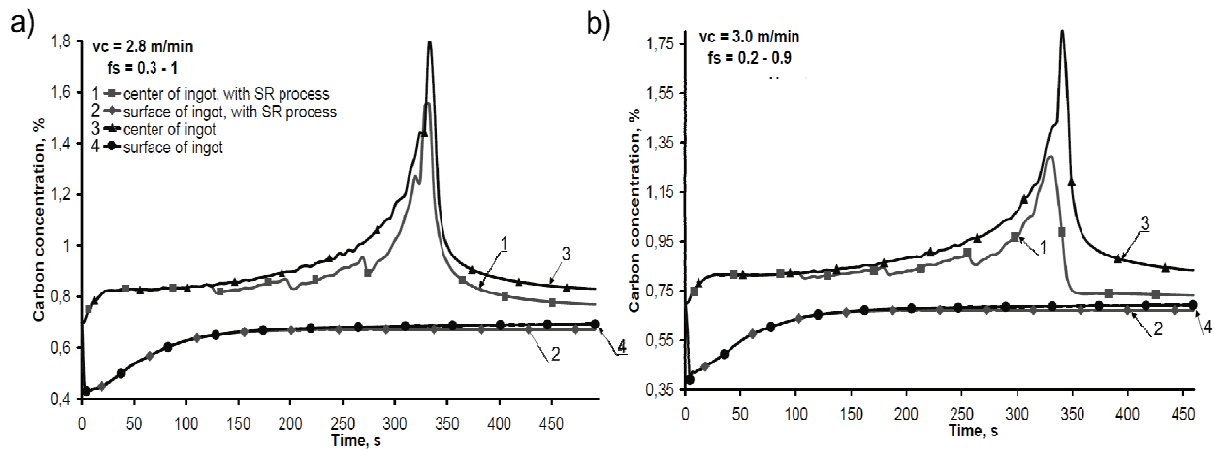

Fig. 2. *Change of carbon concentration during continuous casting process for steel 1: a) for casting speed 2,8 m/min, b) for casting speed 3 m/min.*

Table 2. *Solved carbon concentration based on development numerical model and determine in experimental [2].*

fs			%C$_{center}$	%C$_{surface}$	Δ%C	C$_{center}$ / C$_0$
0.3 – 1.0	conventional	experiment	0.721 – 0.903	-	-	1.03 – 1.29
		solve	0.830	0.692	0.138	1.19
	with SR	experiment	0.679 – 0.798	-	-	0.97 – 1.14
		solve	0.770	0.671	0.099	1.10
0.2 – 0.9	conventional	experiment	0.707 – 0.854	-	-	1.01 – 1.22
		solve	0.833	0.692	0.141	1.19
	with SR	experiment	0.637 – 0.798	-	-	0.91 – 1.14
		solve	0.731	0.671	0.060	1.04

Soft reduction process decrease segregation carbon in each variant what can be observing on figure 2. Difference carbon concentration between surface and center of ingot was 0.098% for variant with soft reduction process at a casting speed of 2.8 m/min. For variant at a casting speed of 3.0 m/min efficiency of soft reduction process was large than first variant (Δ%C = 0.060%). In first variant value of the fraction solid in the core between 0.3 – 1.0, when passing through the reduction zone and it influences on effective alleviation of segregation in billet. The

The influence of solute elements on segregation in CC ingot with soft reduction process was examined in work. For medium carbon steel (table 1) made two variants of simulation CC process (conventional and with soft reduction) at a casting speed of 3.0 m/min. In this cases billet was solidification fast than for steel C72D (figure 4). Range between liquid and solid temperature for medium carbon is lesser than high carbon steel and it is influences on solidification process. In consequence it cause decrease efficiency of soft reduction process on segre-

gation elements in billet. Difference in carbon concentration between the surface and the center of the billet was 0.061% for conventional process and 0.053% for CC process with soft reduction.

2. The numerical results showed that the soft reduction process influences the macrosegregation in the ingot continuous cast. The carbon concentration in steel essentially influences the effectiveness of the soft reduction process in the ingot.
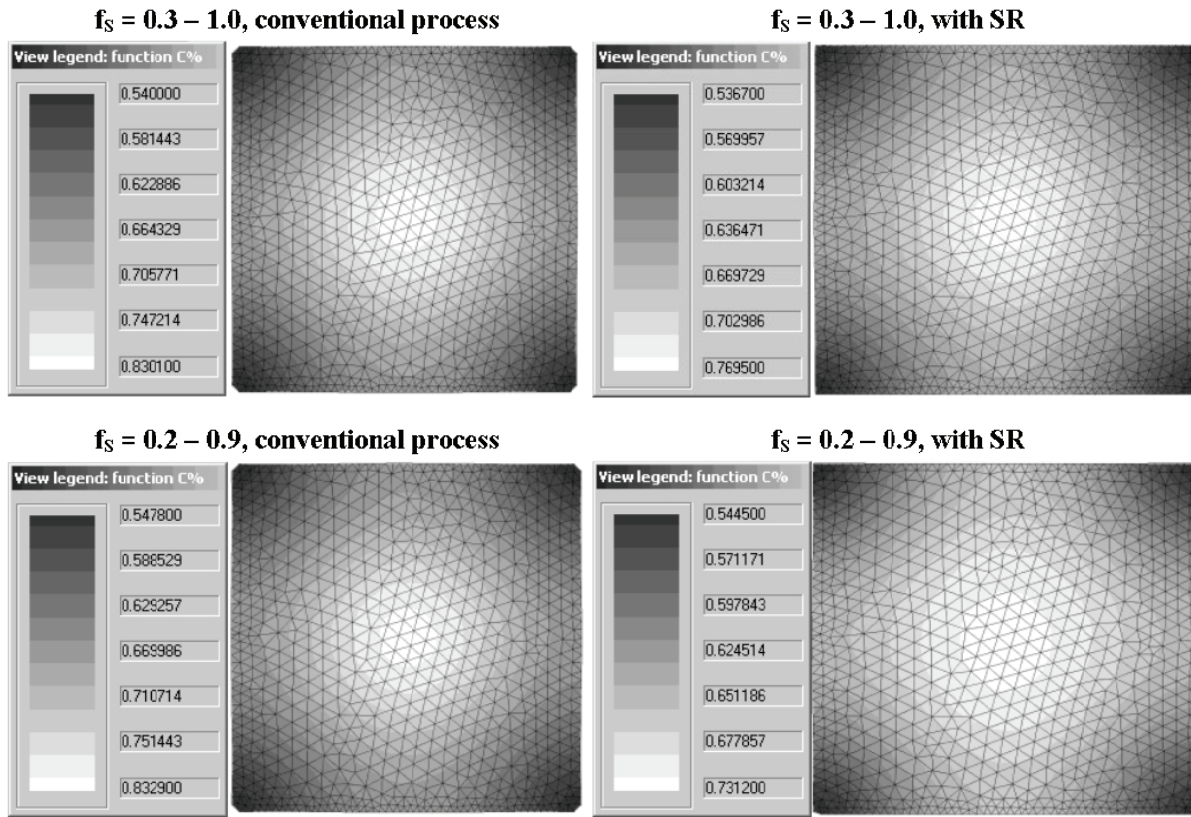

Fig. 3. *Distribution of carbon concentration in the cross-section of continuous cast billet, at the end of continuous casting process for steel C72D.*
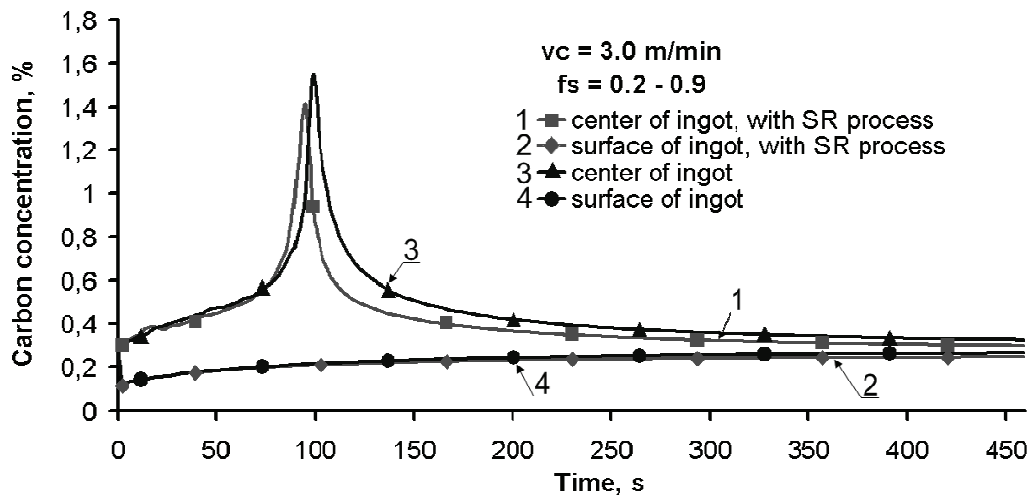

Fig. 4. *Change of carbon concentration during continuous casting process for steel 2.*

4. SUMMARY AND CONCLUSIONS

1. The new model of macrosegregation, in continuously cast ingot, which is taking into consideration the soft reduction process is present.

For high carbon steel the effectiveness of the soft reduction process increase.

3. The agreement between experimental data of macrosegregation in ingot and FEM calculation by elaborated model is reasonably good.

COMPUTER METHODS IN MATERIALS SCIENCE

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NUMERYCZNY MODEL 3D MAKROSEGREGACJI WE WLEWKACH STALOWYCH PODCZAS CIĄGŁEGO ODLEWANIA Z WALCOWANIEM W STANIE PÓŁCIEKŁYM

Streszczenie

Praca prezentuje trójwymiarowy model numeryczny makrosegregacji pierwiastków we wlewku odlewanym w sposób ciągły. Opracowany model numeryczny analizowany jest w odniesieniu do modelowania procesu ciągłego odlewania z walcowaniem w stanie półciekłym (Soft Reduction). W pracy przedstawiono przykładowe symulacje numeryczne makrosegregacji węgla we wlewku. Praca pokazuje wpływ parametrów procesu Soft Reduction na rozwój makrosegregacji pierwiastków we wlewku podczas ciągłego odlewania stali.