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ISSN 0543-5846
METABK 48(2) 71-74 (2009)
UDC – UDK 519.61/.64, 519.86, 624.042, 669.1=111

PHYSICAL MODELING OF STRESSES DURING CONTINUOUS CASTING OF ST3S STEEL

Received – Prispjelo: 2008-01-02
Accepted – Prihvaćeno: 2008-10-25
Original Scientific Paper – Izvorni znanstveni rad

In this work the results of physical and numerical modeling of stresses in metal during continuous casting were shown. The numerical research for St3S ingot were realized. Computer program based on Finite Element Method (FEM) was used to simulation. Investigated conditions were based on actual data received from one of polish steel plant. The simulation of continuous casting process was made on GLEEBLE 3800 simulator. The results of thermal load and also stages of bending and straightening of the bloom and stress relaxation phenomenon were shown. Mechanical properties of a solid metal are described by the theory of dislocation that allows taking into account history of changes of stress and strain in the material.

Key words: theory of dislocation, stress relaxation, numerical modeling, FEM

Fizikalno modeliranje naprezanja tijekom kontinuiranog lijevanja čelika St3S. U radu su prikazani rezultati fizikalnog i numeričkog modeliranja naprezanja u metalu tijekom kontinuiranog lijevanja. Provedeno je numeričko istraživanje ingota St3S. Za simulaciju je rabljen računalni program utemeljen na Metodi konačnih elemenata (MKE). Istraživani uvjeti temelje se na stvarnim podacima dobijenim u jednoj poljskoj čeličani. Simulacija procesa kontinuiranog lijevanja provedena je na simulatoru GLEEBLE 3800. Prikazani su rezultati toplinskog opterećenja a također stadiji savijanja i izravnavanja bluma te fenomen relaksacije naprezanja. Mehanička svojstva krutog metala opisana su uz pomoć teorije dislokacija koja omogućuje uzimanje u obzir prethodne promjene naprezanja i deformacije u metalu.

Ključne riječi: teorija dislokacija; relaksacijska naprezanja; numeričko modeliranje; MKE

INTRODUCTION

During the continuous casting process, a nonstationary stress state forms in the metal, which is caused by a non-uniform temperature distribution, phase transitions, and the deformation of the stock in a semi-liquid state. Stresses occur also as a results of ferrostatic pressure and the deflection and straightening of the continuous casting. In addition to these phenomena, intensive processes of stress relaxation occur in the metal. A prerequisite for obtaining an accurate model of stresses in the metal during continuous casting is to take these phenomena into account. The equations of the model developed are presented in works [1-4].

The numerical analysis carried out in the work was based on the actual conditions of the continuous casting process in a Polish steel mill. Conditions of the mathematical and physical modelling of the process were selected for a 300×400 mm casting of St3S steel.

The aim of the study was to physically model the processes of stress formation and relaxation in metal during continuous casting.

Variations in temperature and strain rate at the characteristic points of the casting cross-section were obtained by using the mathematical model of the thermomechanical state of metal. From computer simulation, conditions for physical modelling on the GLEEBLE 3800 simulator were determined. This machine enables the modelling of the influence of temperature and strain factors on the metal within a wide range of variation of thermomechanical parameters.

DETERMINATION OF THE TEST CONDITIONS USING MATHEMATICAL MODELLING

For the modelling of crystallization processes, the solution of the heat equation, as modified by the effective specific heat method, was used. This method is based on the equation (1) in the following form:

$$c_{eff}(t)\rho(t)\frac{\mathrm{d}t}{\mathrm{d}\tau} = \mathrm{div}(k(t)\mathrm{grad}(t)), \qquad (1)$$

where ρ – metal density; t – alloy temperature; τ – time; c_{eff} – effective specific heat, as determined from the following relationships (2)(3) and (4):

$$c_{eff} = c_s(t) \qquad \forall\ t < t_s \qquad (2)$$

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$$c_{eff} = c_f + L\frac{\mathrm{d}f_s}{\mathrm{d}t} \approx c_f + \frac{L}{t_L - t_S} \qquad \forall\ t_S < t < t_L \qquad (3)$$

$$c_{eff} = c_L \qquad \forall\ t > t_L \qquad (4)$$

c_f – crystallization specific heat, $c_f = f_s c_s + (1-f_s)c_L$, t_L – alloy liquidus temperature; t_s – alloy solidus temperature, L – latent heat of crystallization, f_s – solid phase fraction, c_s – solid phase specific heat, c_L – liquid phase specific heat.

The model considers the plane state of strain, as it is assumed that the strains on the longitudinal section of the casting are equal to zero. The solution of such a state can be achieved by the minimization of the Lagrange functional:

$$J = \int_V E'\Delta\varepsilon_i^2 \mathrm{d}V + \int_V K(\Delta\varepsilon_0 - \beta\Delta t)^2 \mathrm{d}V + \int_V f_L p_f (\Delta\varepsilon_0 - \beta\Delta t)\mathrm{d}V + \int_S \sigma_i \Delta u_i \mathrm{d}S \qquad (5)$$

where: E' – modulus of plasticity.

The algorithm for the solution of the three-dimensional state of thermal conduction and crystallization of continuous casting is based on the step-by-step computation of the plane section as the casting passes through the successive stages of the continuous casting machine, i.e.: through the mould, the secondary cooling section and the air cooling section.

A mould section, the beginning of the secondary cooling zone, and the moment of casting deflection and straightening were considered in the present study. The solution was obtained for two section points situated on the external casting side.

The simulation of temperature variation at those points is shown in Figures 1 and 2. The obtained curves are typical of crystallization: after cooling in the mould, heating up of the surface by internal metal heat in the initial zone of secondary cooling is visible.

TESTING METHODOLOGY AND THE EXPERIMENTAL DETERMINATION OF THE RHEOLOGICAL PROPERTIES OF METAL BY PHYSICAL MODELLING

Specimens made of St2S steel of a length of 120 mm and a diameter of 10 mm were used for tests. Deformation took place in the vacuum chamber of the GLEEBLE 3800 simulator. A uniaxial tensile test was performed. The centre of an approx. 12 mm-long specimen was deformed at variable temperature and variable strain (Figs. 3 & 4). The specimen after a strain of 0,15 is shown in Figure 5. The beginning of the strain variation curve in Figure 3 corresponds to the free elongation of the specimen during heating. Then the specimen was held at a temperature of 1300 °C for a period of 30 seconds, after which the temperature was started to be lowered. After 300 seconds of cooling, modelling of casting deflection was started. The specimen was tensioned until a strain of 0,03 was reached. After 1200 seconds, band straightening followed, and the specimen was compressed with a strain of 0,03, Figure 4.

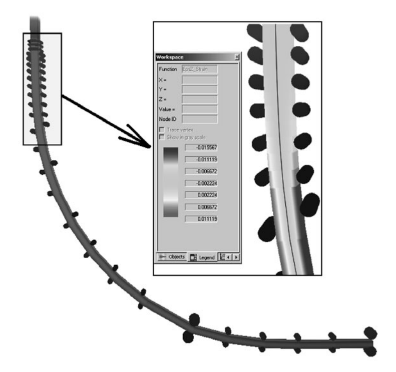

Figure 1. Computed distribution of temperature and strain, ε_zw, in the casting section under consideration

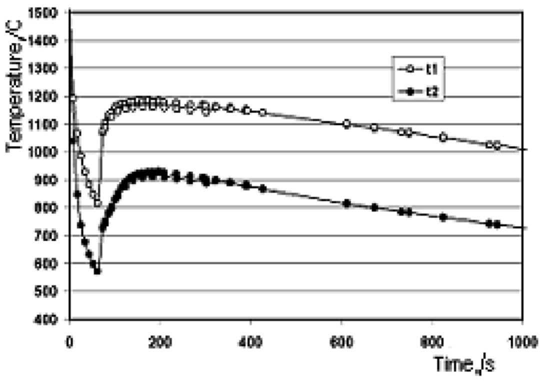

Figure 2. Distribution of temperature variation in the central tensioned casting side (t1) at the corner point (t2)

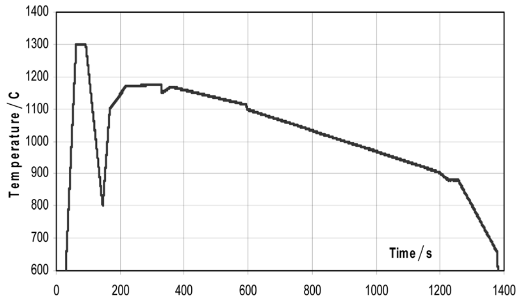

Figure 3. Preset temperature variation in physical modelling

For modelling of the yield stress, σ_S, of steel in continuous casting, we use two different methods. The first of them is based on the theory of dislocation and allows for considering the stress relaxation processes and the non-monotonic behaviour of metal deformation in the CSC machine. This methodology relies on the equations describing the variation of dislocation density and yield stress in the form of: (6) (7) (8):

$$\sigma_S = C_3\sqrt{\rho}, \qquad (6)$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}\tau} = C_1\varepsilon_1 - C_2\rho^2, \qquad (7)$$

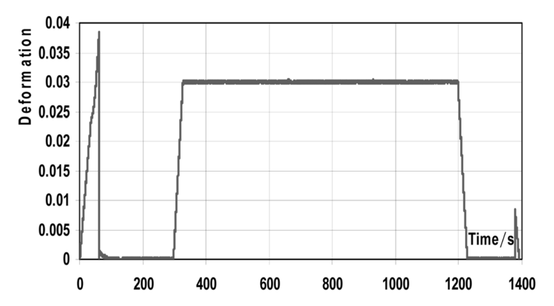

Figure 4. Preset specimen strain variation in physical modelling

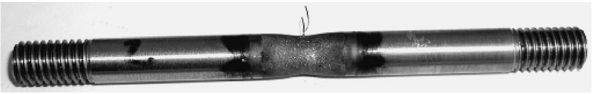

Figure 5. Specimen after deformation

$$C_i = (a_{1i} + a_{2i}\varepsilon_i)\exp(a_{3i}t),\ i=1,3 \qquad (8)$$

where: C_i – model coefficients, a_{ji} – matrix of empirical coefficients, ρ – dislocation density.

The second method relies on the static model of yield stress (9):

$$\sigma_S = \alpha_1 \varepsilon_i^{\alpha_2} \exp(\alpha_3 \varepsilon_i)\varepsilon_i^4 \exp(\alpha_5 t) \qquad (9)$$

where $\alpha_1 - \alpha_5$- are empirical coefficients.

By the processing of the work-hardening curves using the least squares method, the following coefficients of the yield stress models considered were obtained:

- the model based on the dislocation theory equations (6-8):
  a_{11}=3,01; a_{21}=a_{31}=0; a_{21}=0,21; a_{22}=0; a_{23}=0,0002; a_{31}=13000; a_{32}=0; a_{33}=-0,005.
- the model based on equation (9):
  a_1=25970,4; a_2=0,689854; a_3=-7,83501; a_4=0,140671; a_5=-0,00320601

The plots of the computed work-hardening curves are shown in Figures 6-7.

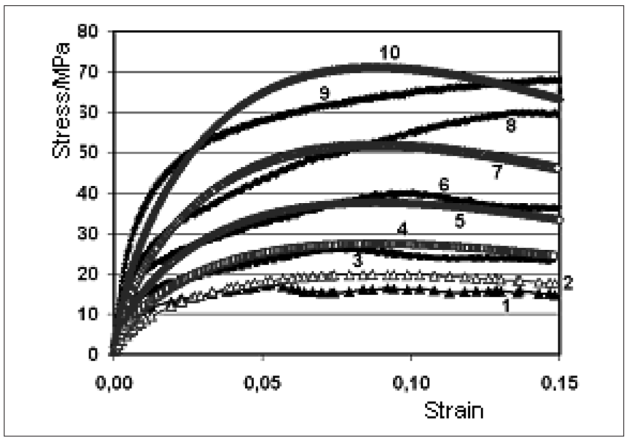

Figure 6. Flow curve for deformation velocity 0,001 s^{-1} (1,2,5,6,9,10) and 0,01 s^{-1} (3,4,7,8) and temperature 1200 ^{0}C (1,2,3,4), 1000 ^{0}C (5,6,7,8), 800 ^{0}C (9,10); (1, 3, 6, 8, 9) – experiment, (2,4,5,7,10) calculated according to equation (9).

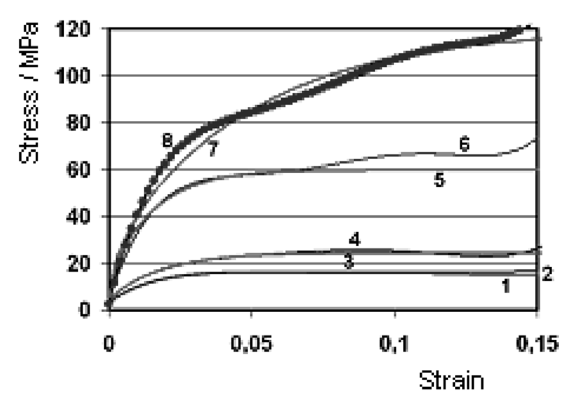

Figure 7. Flow curve for deformation velocity 0,001 s^{-1} (1,2,5,6) and 0,01 s^{-1} (3,4,7,8) and temperature 1200 ^{0}C (1,2,3,4), 800 ^{0}C (5,6,7,8); (1, 3, 6, 8) – experiment, (2,4,5,7) calculated according to equation (6 - 8).

PHYSICAL MODELLING OF THE VARIATION OF STRESS IN THE CASTING DURING CONTINUOUS STEEL CASTING

Testing of the models of mechanical properties based on equations (6-8) and (9) were also carried out using the GLEEBLE 3500 simulator.

The beginning of the stress variation curve, up to point (1) in Figure 8, corresponds to the zero stress during heating the specimen with free displacement capability. A section of compressive stress exists between points 2 and 3. Holding the specimen for a period of 30 seconds results in relaxation of the stress. Then, tensile stress follows, which is caused by the intensive cooling of the metal in the mould (3). After the exit from the mould, in the secondary cooling zone, the heating of the material takes place at the point considered by the internal heat of the casting. Compressive stress forms (4). Due to the relaxation and temperature change phenomena, the stress between points (4) and (5) decreases. Another section of the graph represents the casting deflexion zone, where tensile stress appears (6), relaxing to zero at point (7). During this time, the amount of the liquid metal phase on the cross-section decreases, and the temperature starts to monotonically decrease, causing, at the same time, an increase in the tensile stress (section 7-8). At point (8), the straightening of the casting starts. Compressive stress appears (9). As a result of cooling, stress at point (10) decreases. An allotropic change occurs in the metal at this point. At point (11), the temperature lowers, and a retardation of stress relaxation and cooling rate follows.

The distribution of temperature variation for the simulator was taken from the results of numerical simulation, Figure 9. The first strain rate maximum corresponds to the thermal deformations in the mould, the third – to the exit from the mould and the secondary cooling zone, and the third – to the band deflection zone.

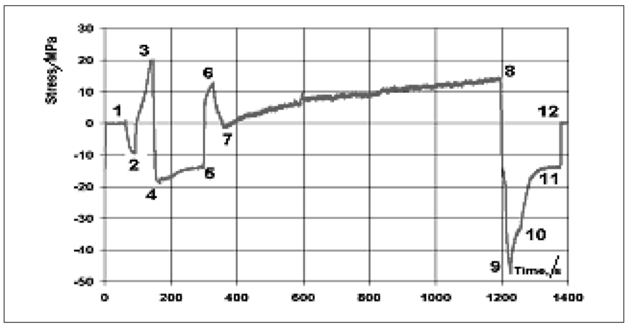

Figure 8. The obtained variation of stress in the sample in physical modelling

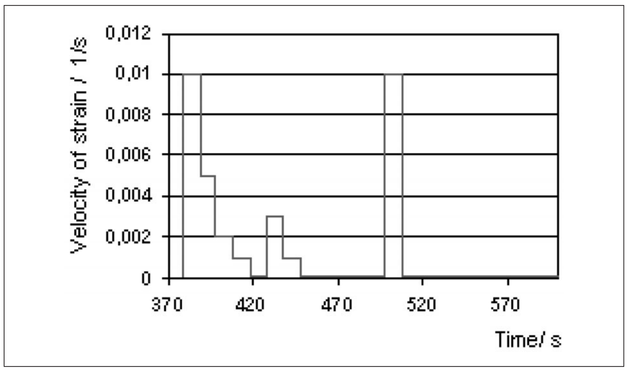

Figure 9. Deformation velocity distribution for physical modelling of metal properties in CCM

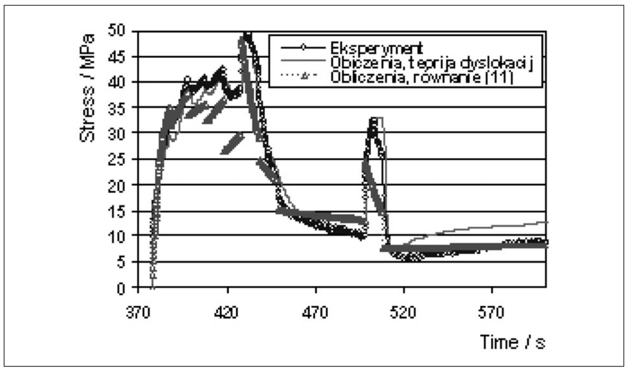

Figure 10. Results of physical modeling of stress in material during continuous casting (curve – „experiment"), distribution according to equation 11 without relaxation (dotted line) and results of distribution according to model on the basis dislocation theory (solid line).

A comparision of the results from the testing of the models based on equations (6 – 8) and (9) with the experimental data for the above described conditions in the CSC machine is shown in Figure 10.

When comparing both model variants, it can be noticed that the modelling with equations (6-8) yields more accurate results. Modelling the work-hardening curve using equation (9) with variable strain rate results in a significant difference between the experimental curve and the theoretical curve in the ranges of intensive strain rate change.

The analysis of the data in this figure allows one to conclude that the static yield stress model (9) cannot be used for the computation of stress in metal during processing in the CSC machine, except for those stages, where the strain varies monotonically.

CONCLUSIONS

A mathematical model of the state of stress and strain in the stock during the continuous steel casting process has been presented in the paper. Two mathematical model variants were employed, respectively, not involving relaxation, and based on the theory of dislocation. By comparing the physical modelling and the mathematical modelling it can be noted that the modelling based on the theory of dislocation better takes the deformation history into account.

In the case of omitting the relaxation phenomenon, an error in the order of magnitudes of 20-30 % can be obtained, and the results are only consistent for monotonic strain.

On the basis of the new method of physical modelling of thermomechanical processes occurring in metal during continuous casting, quantitative data on the change of metal state at the selected point in the casting cross-section have been obtained. It has been demonstrated that the stress at a given point is the result of the influence of thermal loads, the deflection and straightening of the casting in the CSC machine, the stress relaxation processes and the allotropic change in the metal.

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Note: The rensponsible for English language is C. Grochowina.