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THERMO-MECHANICAL MODEL OF STEEL CONTINUOUS CASTING PROCESS

TERMOMECHANICZNY MODEL NUMERYCZNY PROCESU CIĄGŁEGO ODLEWANIA STALI

In the paper a numerical model of heat and mass transfer in the mould zone in the steel continuous casting technology was presented. The model has been developed using ProCAST software designed for simulation of casting processes. It allows to determine temperature and stress distribution in continuous castings in order to optimize the most important process parameters. In this work calculations were executed for low carbon steel grades casted in the industry. In the simulations the real rheological properties measured in the experimental work and the boundary conditions determined on the basis of the industrial data were used.

Keywords: continuous casting process, numerical simulation, rheological model

W pracy przedstawiono numeryczny model przepływu ciepła i masy w strefie krystalizatora w procesie ciągłego odlewania stali. Model ten został opracowany z wykorzystaniem oprogramowania ProCAST przeznaczonego do symulacji procesów odlewniczych. Model ten może służyć do wyznaczenia rozkładu temperatury oraz naprężenia w ciągłym wlewku, co umożliwia optymalizację parametrów procesu. W pracy przeprowadzono symulacje dla stali niskowęglowych. W symulacji wykorzystano rzeczywiste właściwości reologiczne stali wyznaczone w pomiarach laboratoryjnych oraz warunki brzegowe określone na podstawie danych przemysłowych.

1. Introduction

The continuous casting technology is the basic method of steel casting on an industrial scale. It combines both low cost of production and high-quality of obtained steel. Moreover, the CCS reduce the pre-forming operations in a comparison with the traditional casting technology of steel into ingot moulds. The proper parameters of process allow to avoid many internal and surface defects.

The main goal of the work was a development of the numerical model in order to optimize the cooling parameters in the continuous casting processes. In that case, the optimization can be realized without expensive industrial trials. Application of the model also enables to select such parameters which allow to speed up these processes. It is the way of obtaining higher efficiency of the process while maintaining a limited risk of bleedout during casting in the mould area.

In this work ProCast software was used, which is based on the finite element method using both the Eulerian and Lagrangian approach [1,2]. Correctness of the model is guaranteed by using of the real properties of the casted steels investigated on the basis of the experimental measurements. The values of the heat transfer coefficients, used in the simulations, were taken from literature [3]. They have been determined using industrial data.

2. Rheological model

In order to determine the rheological properties of analyzed steels a tensile test method was applied. Determination of the properties was performed in high temperatures in order to predict susceptibility of thin solid layer of the strip below continuous casting mould to cracks which can appear under the influence of metallostatic pressure. The tensile tests were carried out for different temperatures and one value of strain rate. During measurements the stress and the strain were recorded. The tensile tests were performed using Zwick machine. Due to low strain rate, which occurs in a strip during the continuous casting process, executed tests met the requirements of the static tensile test method. According to the valid standard, for registered values of the mod-

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ulus of elasticity, the rate of stress increment for elastic strain was in the range from 2 to 20 N/mm^2s. Above the yield stress the force was measured with strain rate below 0.008 s^{-1}. The analysis included the static tensile tests of four steel grades: UGM, S237, F320 and B500SP. The chemical composition of the alloys is presented in Table 1. The chemical analysis was carried out using the FOUNDRY-MASTER compact emission spectrometer for process-control and the chemical analysis of metals supplied by Worldwide Analytical Systems AG.

The measurements were carried out at three different temperatures: 1000, 1100 and 1150°C. Such range of values corresponds with temperature field occurred for these alloys below continuous casting mould. The samples in the shape of cylinder were 10 mm in diameter and 120 mm in length. They were fixed to the holders using screw joints. The samples were heated using resistance furnace. The chamber of the furnace was filled by protective atmosphere in the form of argon gas.

Graphs of stress – strain curves received within the confines of static tensile tests are shown in Figure 1. The figure consists of four graphs. Each of them presents results for another steel. First shows strain-stress curves for UGM steel, second for S237 steel, third for F320 steel and fourth for B500SP steel. For each steel the measurements were performed at temperatures of 1000, 1100 and 1150°C. The results of measurements allow to draw three conclusions. First of all, increase of temperature causes decrease of the flow stress values. Secondly, most of curves show a decrease of flow stress for higher strain values, what results from recrystallization phenomenon. One can observe also higher extension of the samples at higher temperatures what means increase of steel plasticity. The third conclusion concerns appearance of elastic strain during hot deformation. But obtained results cannot be used for identification of elastic modulus. During the tensile tests the extensometer was not used and it made correct measurement of elongation impossible. This is why the theoretically calculated values of elastic modulus in the numerical simulation were used.

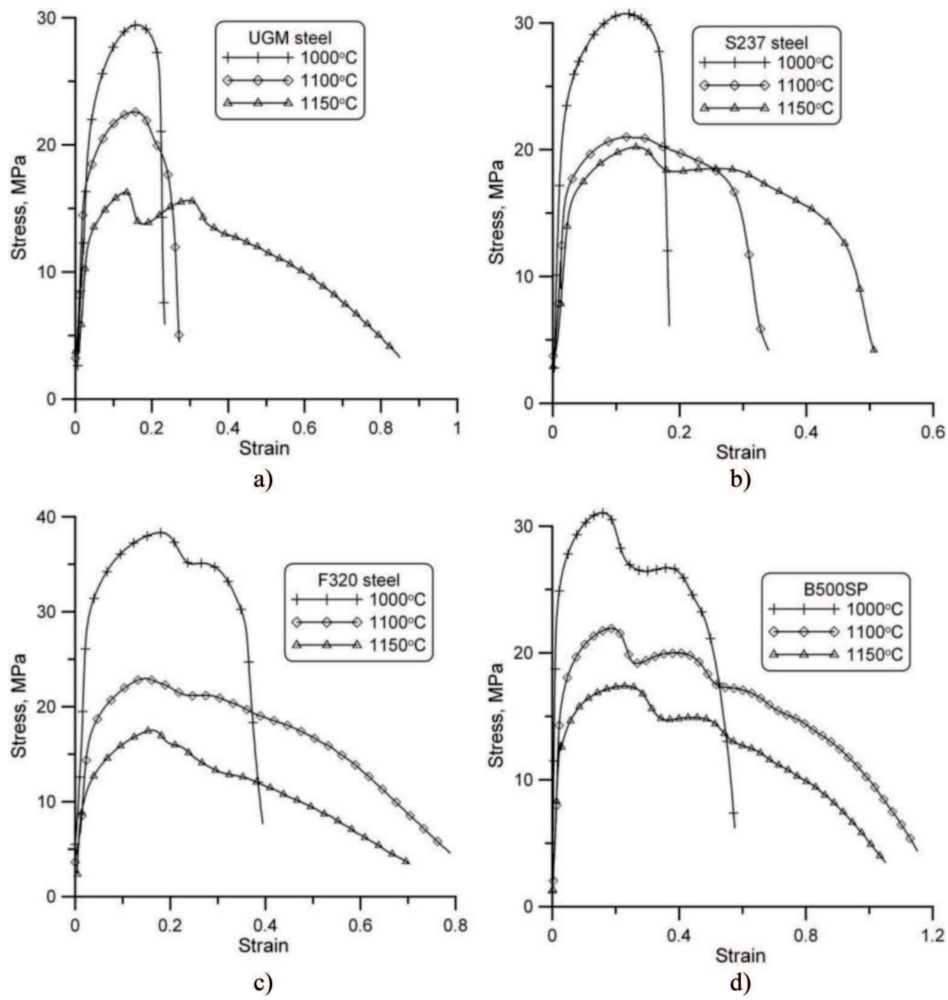

Fig. 1. Graphs of stress – strain curves received within the confines of the static tensile tests performed at temperature of 1000, 1100 and 1150°C: (a) UGM steel, (b) S237 steel, (c) F320 steel, (d) B500SP steel

TABLE 1

The chemical composition of tested alloys: UGM, S237, F320 and B500SP

Steel grade	**Fe**	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**	**Co**	**Cu**
S237	99.2	0.0825	<0.005	0.524	0.0155	0.0142	0.0075	<0.005	0.007	0.0447	0.0029	0.0316
UGM	99.5	0.0492	0.0072	0.213	0.0113	0.0092	0.0076	<0.005	0.0069	0.0369	0.0025	0.031
F320	98.9	0.0966	0.0184	0.736	0.0126	0.0105	0.0209	0.0066	0.0731	0.0282	0.0027	0.0222
B500SP	98.2	0.253	0.171	0.792	0.0187	0.0297	0.0833	0.01	0.0827	<0.005	0.01	0.235
	Nb	**Ti**	**V**	**W**	**Pb**	**Sn**	**B**	**Ca**	**Zr**	**As**	**Bi**	
S237	<0.002	<0.002	<0.002	<0.015	<0.025	<0.002	<0.001	0.0003	<0.002	0.0068	<0.03	
UGM	<0.002	<0.002	<0.002	<0.015	<0.025	<0.002	<0.001	0.0005	<0.002	0.0075	<0.03	
F320	<0.002	<0.002	0.0027	<0.015	<0.025	<0.002	<0.001	0.0003	<0.002	0.0069	<0.03	
B500SP	<0.005	<0.001	<0.005	<0.025	<0.05							

In order to approximate the measured stress-strain curves the elasto-plastic rheological model with power law hardening was applied [4]:

$$\sigma = \sigma_\infty + (\sigma_0 - \sigma_\infty)\, e^{-\alpha \varepsilon_{pl}} \qquad (1)$$

where: σ_0 – yield stress, σ_∞ – ultimate yield stress, α - hardening exponent, ε_{pl} – plastic strain.

The values of model parameters were estimated using approximation with the help of minimum chi-square method. The fitting was carried out using Grapher software. The approximation was based on the minimization of the goal function using optimization methods [5].

The results of approximation are shown in Table 2 where each steel grade has three sets of model parameters, each for another temperature.

In Figure 2 the graphs of stress – strain curves measured in experiments and calculated using rheological model with non-linear hardening (1) are shown.

TABLE 2

The parameters values of rheological model (1) for tested alloys: UGM, S237, F320 and B500SP

Steel	T, °C	E, MPa	σ_0, MPa	σ_∞, MPa	α
S237	1000	1679.05	10.99	30.49	43.50
	1100	883.40	9.21	20.99	39.57
	1150	632.45	7.59	20.22	32.10
UGM	1000	585.42	5.48	29.51	26.41
	1100	769.06	10.09	22.42	26.94
	1150	397.60	6.60	16.45	24.60
F320	1000	1233.83	22.75	38.76	19.11
	1100	636.69	10.45	23.52	20.82
	1150	721.44	7.16	18.14	17.03
B500SP	1000	2213.31	18.33	31.00	28.81
	1100	642.00	11.45	22.20	19.38
	1150	605.64	9.67	17.54	17.24

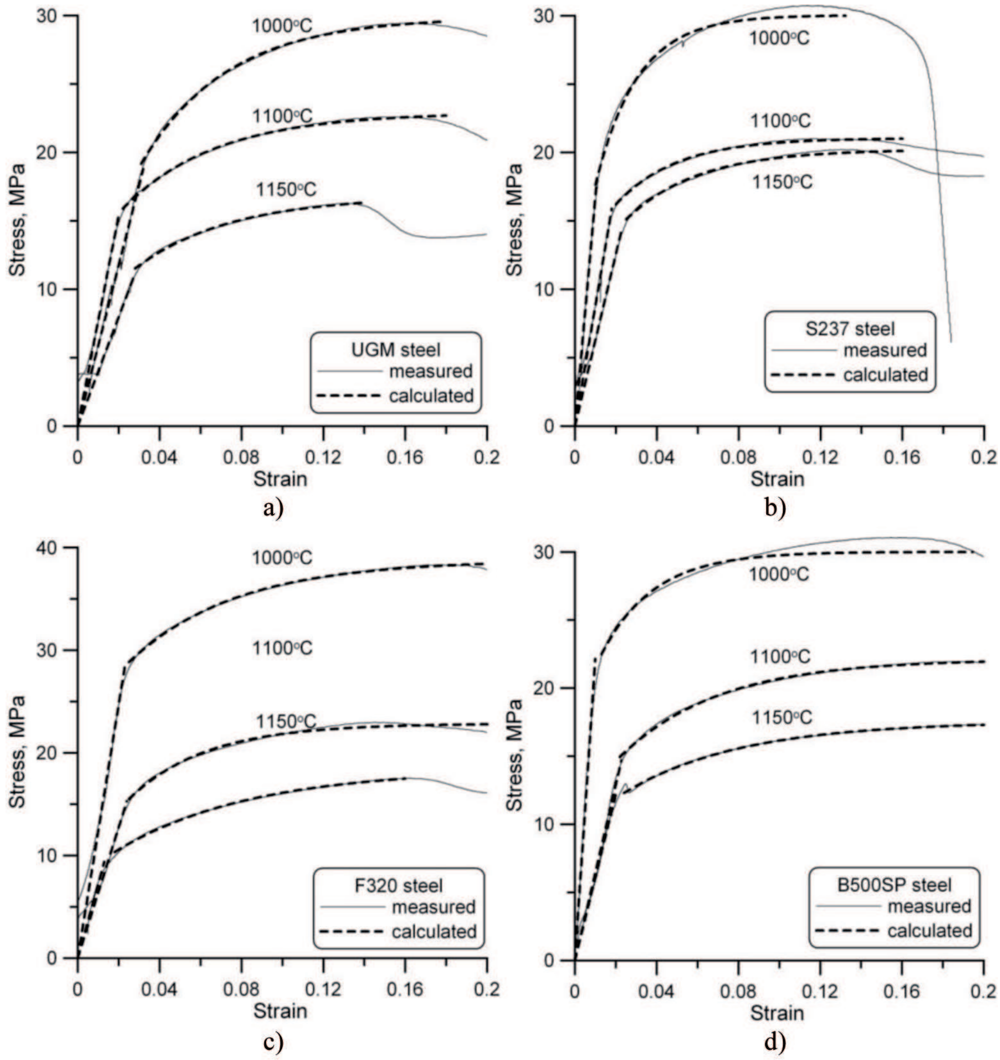

Fig. 2. Graphs of stress – strain curves measured in the experiments and calculated using rheological model with non-linear hardening (1): (a) UGM steel, (b) S237 steel, (c) F320 steel, (d) B500SP steel

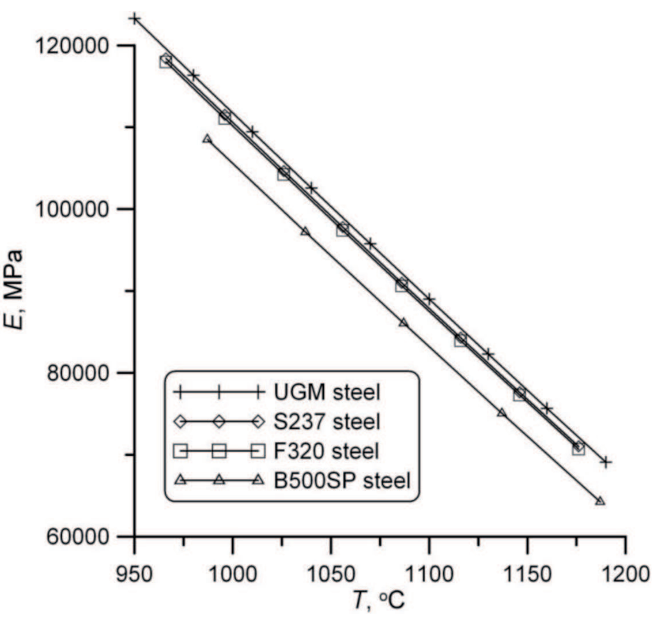

Fig. 3. Elastic modulus versus temperature for: (a) UGM steel, (b) S237 steel, (c) F320 steel, (d) B500SP steel

In view of the inaccurate measurement of samples extension, determined values of elastic modulus are flawed. This is why, in the simulations of the continuous casting process the calculated values of elastic modulus were used (Figure 3). The values were theoretically determined using thermodynamic calculation.

3. Assumptions of numerical model

The boundary conditions used for description of the cooling process of the continuous castings were determined on the basis of industrial data. The first approximation of the heat transfer coefficients was determined using the knowledge of water quantity consumed in the cooling process in the primary and the secondary cooling zone (respectively in the crystallizer and below the crystallizer). The second approximation was obtained by decrease of differences between calculated and measured temperatures on the castings surfaces. In the simulations the following values were assumed:

- heat transfer coefficient between mould and steel – 1050 W/(m^{2}K),
- heat transfer coefficient between mould and its surroundings (primary cooling zone) – 6000 W/(m^{2}K),
- heat transfer coefficient in the secondary cooling zone (between the band and water and air) – 300 W/(m^{2}K).

The thermophysical properties of analyzed steels were determined on the basis of the laboratory measurements. For example the thermal conductivity for four steel grades are shown in Figure 4. Rheological parameters are described in the previous section. The casting speed amounted to 10 mm/s.

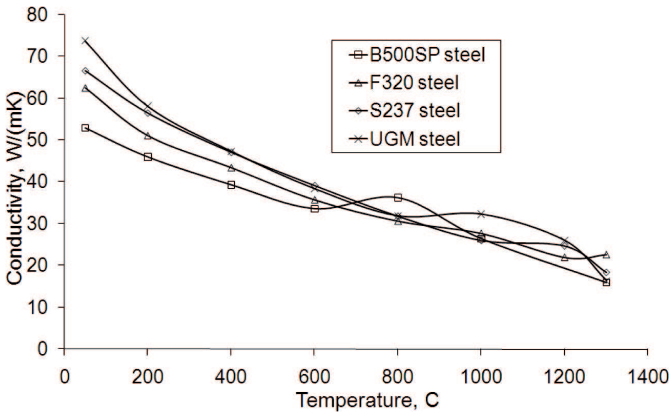

Fig. 4. Conductivity of steel for the four test grades

4. Simulation of continuous casting

The simulations of the continuous casting process have been done using ProCast software. In order to simulate the stress in the castings the mixed Euler-Lagrange model (MiLE) was used, which relies on a combination of Euler and Lagrange finite element mesh. Unfortunately, the current version of the ProCAST software allows to simulate, using the MILE method, only straight shape of the castings. Therefore, the solidification process can be analysed inside a continuous casting mould and directly below it. Taking into account that the greatest danger of interruption of a band is just below the mould, this restriction does not cause negative effects on the correctness of simulation results. The simulations were performed for three sets of parameters. The first set is described in details in previous section. The second set differs from previous one in higher value of the casting speed, that equals 13 mm/s. The third set of parameters differs from the first one in higher intensity of the cooling process. In this case the heat transfer coefficient in the primary cooling zone amounts to 10 000 W/m^{2}K and in the secondary cooling zone amounts to 500 W/m^{2}K.

Figures 5-8 show the distribution of temperature, stress intensity, gap between the mould and the ingot and solid fraction. For the purposes of better visualization crystallizer was moved away from the ingot. The results of simulations (Figures 5-8) shows that increase of casting speed causes:

– increase of ingot temperature

– decrease of thickness of solid (skin) layer below continuous casting mould,

– decrease of stress intensity on the ingot surface,

– decrease of a gap width between the mold and the casting.

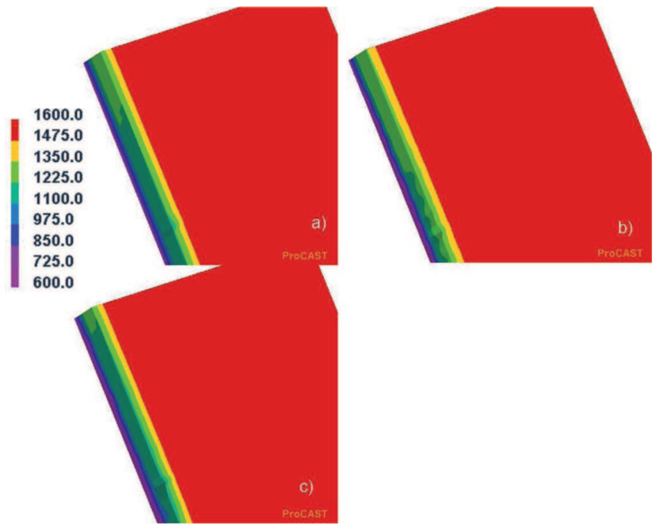

Fig. 5. The temperature distribution (°C) for: a) the reference parameters, b) increased casting speed, c) increased the intensity of cooling

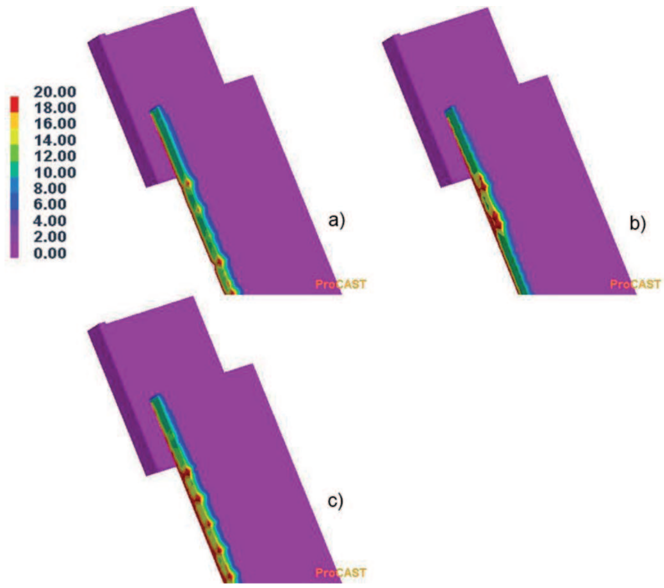

Fig. 6. The effective stress distribution (MPa) for: a) the reference parameters, b) increased casting speed, c) increased the intensity of cooling

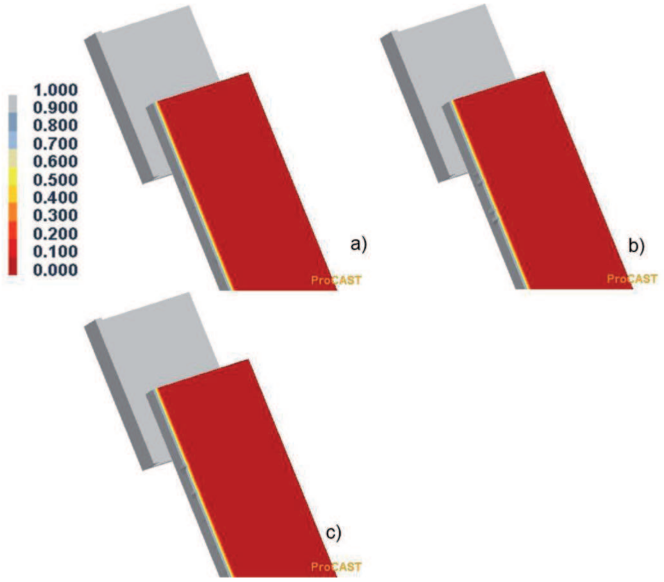

Fig. 7. The fraction solid distribution for: a) the reference parameters, b) increased casting speed, c) increased the intensity of cooling

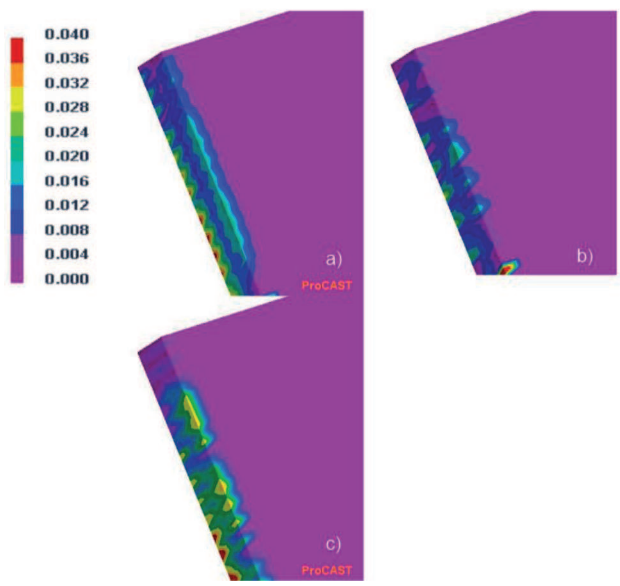

Fig. 8. The gap width distribution [cm] for: a) the reference parameters, b) increased casting speed, c) increased the intensity of cooling

The performed research includes also a comparison between results of simulations for all casted steel grades (see Table 2). For the grades with a higher values of the thermal conductivity temperature of the casting surface is higher and the gap between the ingot and the mould is thinner. Additionally, slower drop of temperature gives lower values of stresses. The Figures 9-12 show the results of simulations for investigated steel grades.

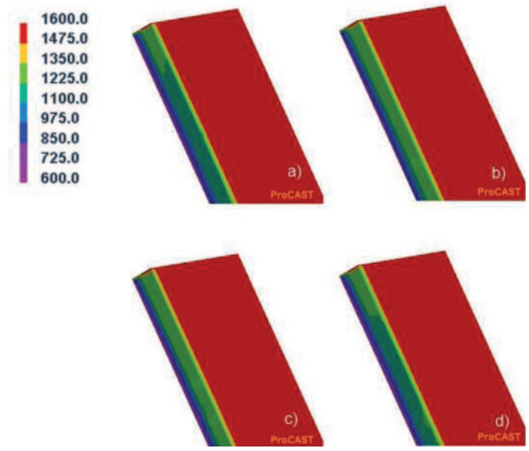

Fig. 9. The temperature distribution [°C] for steel: a) S237, b) B500SP, c) F320, d) UGM

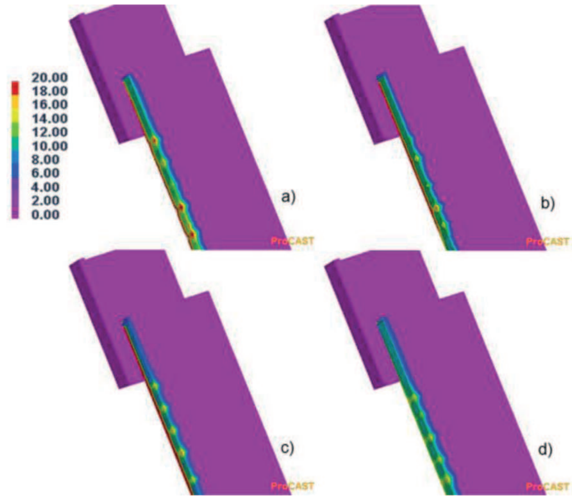

Fig. 10. The effective stress distribution [MPa] for steel: a) S237, b) B500SP, c) F320, d) UGM

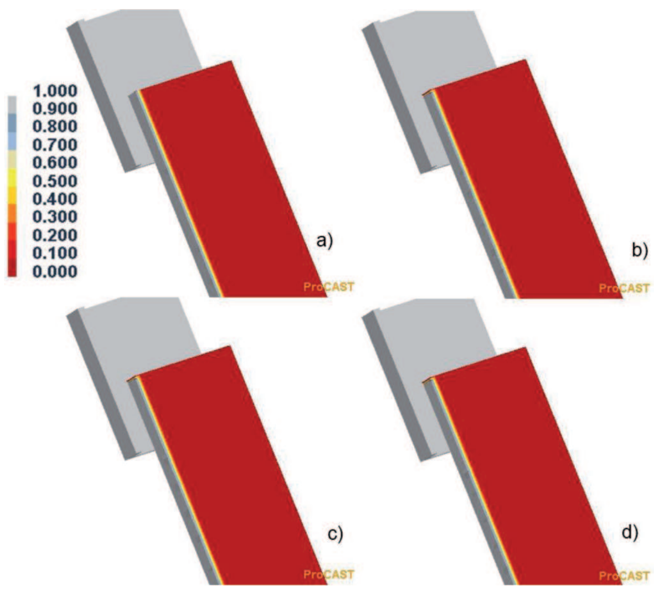

Fig. 11. The solid fraction distribution for steel: a) S237, b) B500SP, c) F320, d) UGM

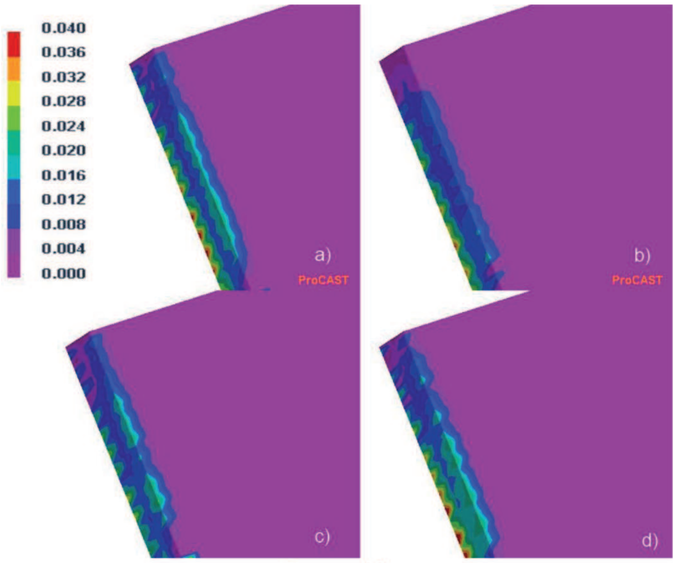

Fig. 12. The width of gap between the ingot and the mould [cm] for steel: a) S237, b) B500SP, c) F320, d) UGM

5. Conclusions

Within the confines of the work the numerical model of the solidification process in the zone of continuous casting mould was developed. It is the thermo-mechanical model which enables to predict the temperature and the stress distribution inside continuous ingots.

The model can be used in optimization of the casting process. In particular optimization concerns possibility of an increase of the casting speed, what can increase process efficiency. But, in that case, the limitation in the form of thinner and weaker solid skin should be considered. Increase of the casting speed causes increase of the steel temperature and decrease of the thickness of the solid skin, what is associated with a greater probability of the bleedout and the steel leakage. In turn an increase of the cooling intensity causes the opposite process, i.e. the casting temperature decreases and the thickness of the solid skin of the casting becomes higher.

The developed numerical model of the continuous casting uses experimentally measured values of the material properties. In that case, the simulations based on the model allow to determine the stress and strain distribution with a higher accuracy. It can help to predict the optimal conditions for the continuous casting of steel.

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REFERENCES

[1] Website, http://www.esi-group.com/products/casting/procast, 2011.
[2] Y.-C. Wang, D.-Y. Li, Y.-H. Peng, L.-G. Zhu, Computational modeling and control system of continuous casting process, International Journal of Advanced Manufacturing Technology, 33(1), 1-6 (2007).
[3] M. Rywotycki, K. Miłkowska-Piszczek, L. Trębacz, Identification of the boundary conditions in the continuous casting of steel, Proc. 5th Int. Conf. Ciągłe Odlewanie Stali, 106-113 Krynica 2011.
[4] ProCAST User Manual, version 2010.0
[5] M. Kopernik, M. Spychalski, K.J. Kurzydłowski, M. Pietrzyk, Numerical identification of material model for C-Mn steel using micro-indentation test, Materials Science and Technology **24**, 369-375 (2008).

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