A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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AN ANALYSIS OF THE INFLUENCE OF VISCOSITY ON THE NUMERICAL SIMULATION OF TEMPERATURE DISTRIBUTION, AS DEMONSTRATED BY THE CC PROCESS

ANALIZA WPŁYWU LEPKOŚCI NA SYMULACJĘ NUMERYCZNĄ ROZKŁADU TEMPERATURY NA PRZYKŁADZIE PROCESU CIĄGŁEGO ODLEWANIA

The numerical modelling of casting processes is based on complex software packages, which most often use the finite element method. But the degree of complexity of the applied model may cause an occurrence of numerical errors. These errors may be generated both by an incorrect finite element mesh and by the use of incorrect material characteristics. The ProCAST numerical software package was used for numerical calculations.

A 3D model was developed on the basis of the process parameters of an actual continuous steel casting process. The temperature distribution of a solidifying strand, with dimensions of 220×1100mm, was analysed for two steel grades: F320 and S235. A series of numerical simulations were performed where the influence of the applied viscosity values on the solidifying strand temperature distribution was presented.

Viscosity values from rheological examinations that were performed with an FRS1600 high-temperature rheometer were used in the numerical simulations of the CC process. The aforementioned rotational measurements were carried out for the F320 and S235 steels in the liquid and in the semi-solid statesto examine the influence of temperature on the viscosity value changes obtained. A concentric cylinder systems working in accordance with Searle's method was used for the measurements.

Numerical calculations that were based on the viscosity values from the CompuTherm LLC, thermodynamic database were compared with one other in the project. The calculated temperature distribution of the solidifying CC strand was verified on the basis of a database that was created during measurements which were conducted in industrial conditions.

Keywords: continuous steel casting, numerical modelling, viscosity, rheology, ProCAST

Modelowanie numeryczne procesów odlewniczych bazuje na złożonych pakietach oprogramowania wykorzystujących najczęściej metodę elementów skończonych. Stopień złożoności zastosowanego modelu może spowodować powstanie błędów numerycznych. Błędy mogą być generowane zarówno przez niewłaściwą siatkę elementów skończonych jak również przez zastosowanie niepoprawnych właściwości materiałowych. Do przeprowadzenia obliczeń numerycznych wykorzystano pakiet oprogramowania numerycznego ProCAST.

Model 3D został opracowany na podstawie parametrów technologicznych rzeczywistego procesu COS. Analizowano rozkład temperatury krzepnącego pasma o wymiarach 220×1100 mm dla stali F320 oraz S235. Przeprowadzono szereg symulacji numerycznych, w których przedstawiono wpływ zastosowanych wartości lepkości na rozkład temperatury krzepnącego pasma.

W symulacjach numerycznych procesu COS wykorzystano wartości lepkości pochodzące z badań reologicznych wykonanych przy użyciu reometru wysokotemperaturowego FRS1600. Powyższe rotacyjne pomiary przeprowadzono dla stali F320 i S235 znajdujących się w stanie ciekłym oraz stało-ciekłym badając wpływ temperatury na uzyskiwane zmiany wartości lepkości. Do pomiarów wykorzystano układ koncentrycznych cylindrów typu Searle'a.

W pracy porównano również obliczenia numeryczne wykonane na podstawie wartości lepkości pochodzących z termodynamicznej bazy danych PANDAT, CompuTherm LLC. Weryfikacja obliczonego rozkładu temperatury krzepnącego pasma COS została wykonana w oparciu o bazę danych utworzoną podczas pomiarów przeprowadzonych w warunkach przemysłowych.

1. Preface

Currently in the modelling of metallurgical processes or calculation material-related parameters, the finite element method, the boundary element method, cellular automata, artificial intelligence algorithms or a combination of these methods through multi-scale modelling [1-3] could be used. Many authors deal with the modelling of casting processes, in particular, the steel continuous casting process, and both commercial packages and original programs [4-11] are used for this purpose. Numerical software packages are most often based on the finite element method.

The construction of the numerical model as regards the CC process involves developing a proper geometry model of the strand – along with the mould – and implementing a finite element mesh. It is also necessary to be familiar with

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the material-related parameters for the cast steel grade, i.e. its specific heat, heat of solidification, thermal conductivity, viscosity, density, and the liquidus and solidus temperatures. In addition, the continuous casting process simulation requires developing a heat transfer model for the primary and secondary cooling zones.

The numerical model calculations were verified by comparing the results of the strand temperature distribution, the shell thickness, and the metallurgical length with an industrial database that was created during measurements carried out in industrial conditions. The verified model enabled the influence of viscosity values – as a function of temperature on the solidifying CC strand temperature field distribution – to be examined. The values of viscosity were measured during rheological examinations performed with an FRS1600 high-temperature rheometer. Rotational measurements were performed on two steel grades in their liquid and semi-solid states, S235 and F320, in order to examine the influence of temperatures on the viscosity value changes obtained.

2. Material-related parameters

The following thermal properties of the S235 and F320 steel from the author's own research: the specific heat along with the heat of solidification, thermal conductivity and viscosity were used for the numerical calculations as regards the temperature distribution of the solidifying continuously cast strand. The values of the liquidus and solidus temperatures (along with the density) were determined on the basis of the chemical composition of the steel examined with the CompuTherm LLC thermodynamic databases that were provided with the ProCAST software package. Table 1 presents the chemical composition of the analysed S235 steel, Table 2 contains the chemical composition of the F320 grade.

TABLE 1

The chemical composition of the S235 steel

C	Mn	Si	P	S	Cr	Ni	Cu	Al	N
0.07	0.76	0.006	0.016	0.0110	0.03	0.06	0.03	0.041	0.0053

TABLE 2

The chemical composition of the F320 steel

C	Mn	Si	P	S	Cr	Ni	Cu	Al	V	Mo
0.07	0.6	0.03	0.02	0.018	0.15	0.15	0.15	0.045	0.02	0.05

The ProCAST software package used for the calculations of the temperature distribution employs the enthalpy method in order to solve the set problem, and this method is described in the equation [12,13]:

$$H(T) = \int_0^T c_p(T)\,dt + L(1 - f_s) \qquad (1)$$

where:

H – enthalpy kJ/kg

c_p – specific heat, kJ/(kgK)

L – transformation heat kJ/kg

F_S – share of solid phase

The value of enthalpy or the values of specific heat along with the heat of solidification should be specified as material-related parameters. The values of specific heat and heat of solidification were implemented in the developed numerical model. Fig. 1 presents the specific heat values as a function of temperature for the S235 steel, Fig. 2 presents the specific heat values as a function of temperature for the F320 steel.

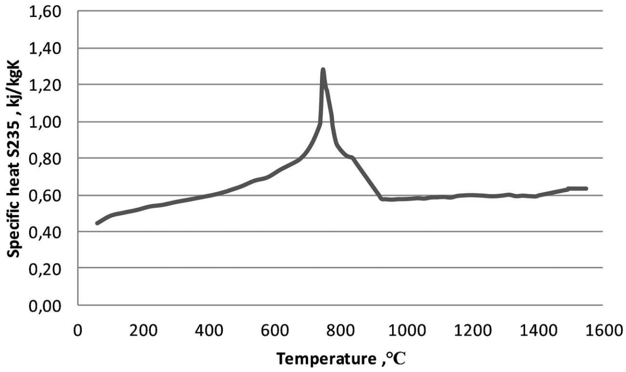

Fig. 1. Specific heat versus temperature for the S235 steel

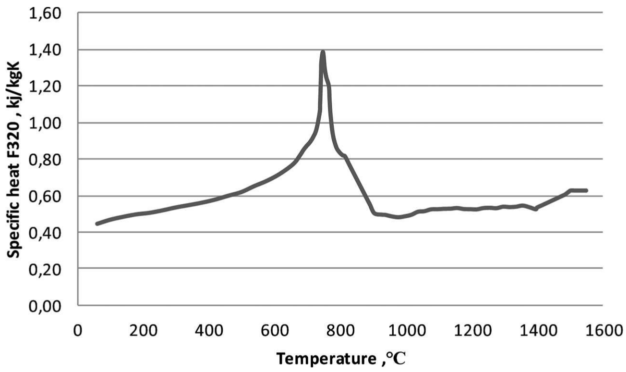

Fig. 2. Specific heat versus temperature for the F320 steel

The heat conductivity values as a function of temperature are presented in Fig. 3 and 4.

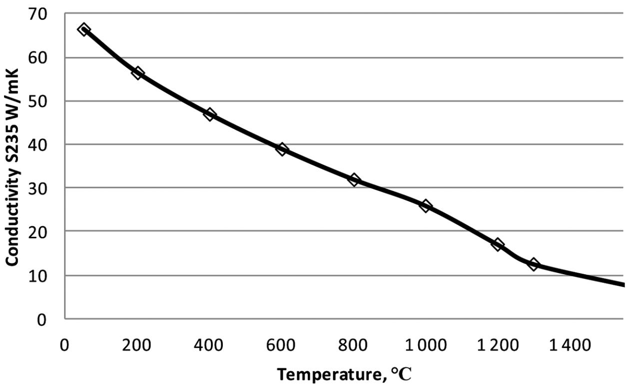

Fig. 3. Thermal conductivity versus temperature for the S235 steel

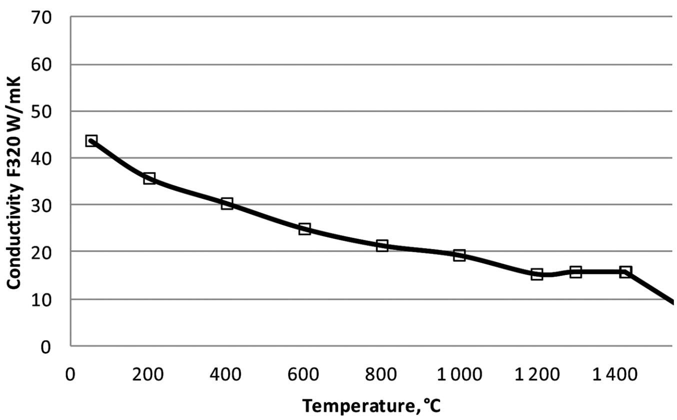

Fig. 4. Thermal conductivity versus temperature for the F320 steel

The values of viscosity for the S235 and F320 steels were calculated on the basis of Newton's law (equation 2), using a thermodynamic database. Figs. 5 and 6 show the viscosity values as a function of temperature as determined with the ProCAST software for the two examined steel grades.

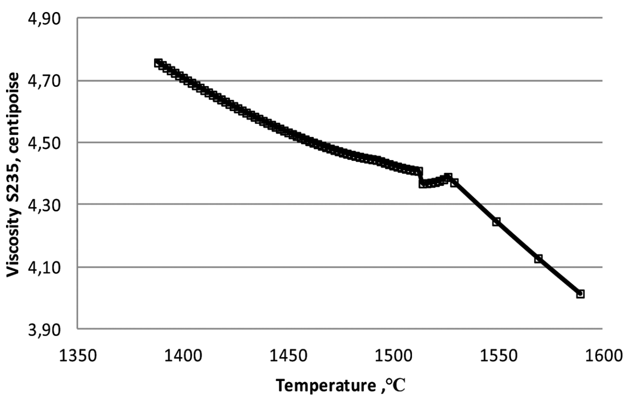

Fig. 5. Viscosity versus temperature for the S235 steel

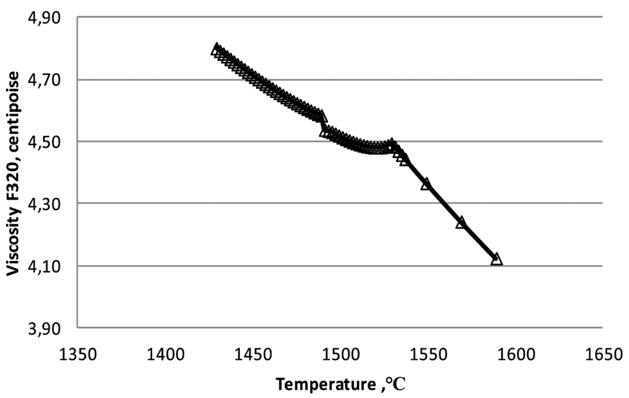

Fig. 6. Viscosity versus temperature for the F320 steel

The value of the heat of solidification for the S235 steel, as assumed in the calculations, is 113kJ/kg. Its liquidus temperature is 1527°C, while its solidus temperature is 1386°C. The value of the heat of solidification for the F320 steel is 124.1kJ/kg. Its solidus temperature has been calculated on the basis of its chemical composition being 1428°C, and its liquidus temperature 1530°C.

3. Viscosity values as a function of temperature

Rheology is a branch of science which has developed as a branch of physics. Today it is an independent field of knowledge, and for over 70 years has dealt with research on the responses of real substances to stresses. This science describes phenomena that occur in a very broad area between the solid and liquid states, so it may be considered a science that deals with the behaviour of real substances, which when subjected to strain, show more than one basic rheological property: elasticity or viscosity. It is an interdisciplinary science, and therefore the approaches, the types of research methods applied, and the ways of rheological research finding utilization, are fairly diversified. However, the main objective of rheology is to develop models for the description of behaviours of bodies that have been subjected to a force impact. Descriptions of the behaviour of ideal solid and liquid bodies have been formulated in the form of mathematical models that have taken into account the relationship between the stress, strain, strain velocity, and the stress growth velocity (rheological function – Hersey 1932).

In 1676, Robert Hooke formulated a law describing the behaviour of an ideally elastic body, where the applied stress was proportional to the strain. In 1687 Isaac Newton considered the phenomena of fluid resistance during spindle rotation in a vessel. His research resulted in an equation that describes the behaviour of an ideally viscous fluid (equation 2). In 1855 Adhémar Jean de Saint-Venant formulated a law describing the behaviour of an ideally plastic body.

Rheometry is a branch of rheology that deals with the measurements of rheological properties by using suitable tools. Rheological properties are the parameters that describe the fluid flow [14].

Rheological tests of steel are innovative tests, but due to technical reasons are difficult to carry out. The following are among the main problems related to making rheological measurements of liquid iron alloys: the high melting temperature of the medium tested, the high reactivity of steel – in particular its oxidability and relatively high costs of experimentation – related mostly to the production (little dimensional tolerances, complex geometry), and the short life of tools used for the aforementioned experiments. The innovativeness of rheological measurements of steel lies in the possibility of developing an experiment using modern measuring instrumentation, that being a high-temperature rheometer. This device, equipped with a furnace, enables the tested alloy to be heated to a desired temperature (over 1500°C), the temperature to be controlled during a measurement, and the value of the force acting on the medium tested to be continuously changed.

A high-temperature rheometer, also known as an absolute multi-point viscometer [14] is a versatile device for the testing of both Newtonian and non-Newtonian fluids. Until recently, research on liquid alloys with high melting temperatures was not possible due to the unavailability of suitable measurement instrumentation: viscometers enabled a single-point measurement of relative viscosity in low temperatures. For measurements made with traditional viscometers, it was not possible to act on a medium tested with various forces, and subsequently prohibited the testing of non-Newtonian fluids.

At the moment the prevailing view defines liquid steel as a Newtonian fluid that is subject only to changes in temperature, pressure and chemical composition. The objective of projects [15-19] undertaken by their authors was to verify the existing knowledge on viscosity of liquid steel, and to expand on this knowledge by conducting rheological research on iron alloys in its fully liquid and semi-liquid states.

Viscosity is a property of a solid, liquid and gaseous body that ensures the speed of change in the body shape is proportional to shear stresses existing in this body. It is a property of fluids, gases and plastic solids, and characterises their internal resistance to flowing. Viscosity is defined for a laminar kind of flow, which in a simplified way, describes the flow of layers that do not undergo mixing – such a flow occurs at low speeds. It is also characterised by its ability to transfer momentum between the adjacent layers of fluid that move with various speeds. This effect occurs as a result of the shear stresses that appear at the borders. The difference in layer speeds is described by the so-called shear rate:

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{2}$$

where:

η– dynamic viscosity, Pa·s

τ– shear stress, Pa

$\dot{\gamma}$– shear rate, s^{-1}.

The conducted rotational rheological measurements were aimed at determining the changes in the viscosity value of the selected steel grades as a function of temperature. The tests were made with a FRS1600 high-temperature rheometer, which is presented diagrammatically in Fig. 7, and this enabled measurements to be conducted up to a temperature of ca. 1560°C.

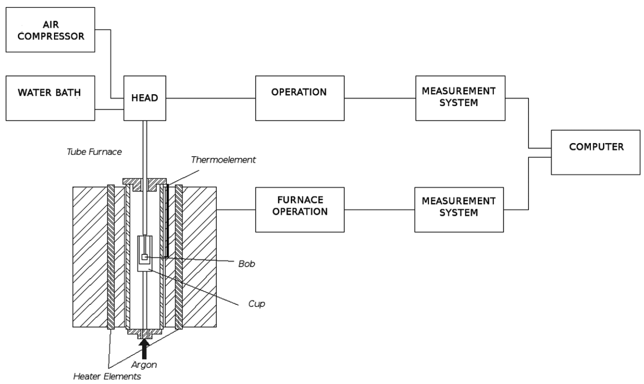

Fig. 7. A diagram of a FRS1600 high-temperature rheometer

The above rheometer operates in a concentric cylinder system, with a rotary internal cylinder. The device has an air bearing, enabling very accurate measurements to be taken.

Materials for the measurement tools were selected to prevent reaction of the tool surface the sample tested. The measurement system was made of aluminium oxide, with the addition of zirconium dioxide that was used to stabilize the material at rapid temperature changes.

Prior to measurement, calibration oil – with low viscosity values (under 1 Pa·s) – was used on the cylinder system, the calibration being the basis for selecting the correct values of the so-called conversion factors, C_{sr} and C_{ss}, as considered in the following equations [20]:

$$\tau = C_{SS} \cdot M \tag{3}$$

$$\dot{\gamma} = C_{SR} \cdot n \tag{4}$$

where:

τ– shear stress, Pa

$\dot{\gamma}$– shear rate, s^{-1}

M – torque, Nm

n – speed of rotation, rpm.

The measurements were made for the F320 and S235 alloys in the liquid and in its semi-solid state. A system with a small rheological gap (1.7 mm) was used for tests in the liquidus conditions. For measurements in the semi-solid state, a spindle with a smaller diameter was used, causing the gap between the cylinders to increase by up to 7.0 mm. In each case the tests were carried out until ”the spindle stopped”, resulting in an increase in torque above the maximum value (200 mNm).

The viscosity values obtained during the cooling of the alloy from 20 degrees above the liquidus temperature, to the temperature in which the torque of the device reached its maximum value, are presented in the Fig. 8:

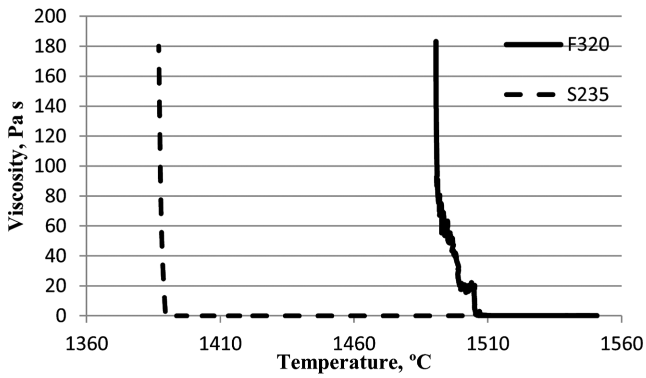

Fig. 8. Viscosity versus temperature for the F320 and S235 steels

For the F320, the viscosity was measured over a temperature range of 1550-1490°C, and for S325 between 1550-1390°C. The samples tested were first heated to a temperature of 1550°C after which, during the reduction of the temperature at a rate of ca. 1 °C/minute, the viscosity was measured and its values read every minute. In the above temperature ranges, the viscosity values increased from millesimal parts of pascal-seconds to about 180 Pa·s (at the lowest of the temperatures tested). For the F320 alloy, the first substantial increase in the viscosity value was at a temperature of about 1510 °C; the increase for the S235 alloy was for a temperature of about 1400°C. In both cases – after the first noticeable jump in viscosity values – the alloy viscosity values went up; however, for the S235 alloy, this jump was much higher (rapid) – no ‘gradual’ increase in the value was observed. This discrepancy concerning the temperature values at which the rapid change in the viscosity value for the steels tested probably occurred as a result of the differences in the chemical composition of the alloys (other conditions of the experiment were identical), which is in line with theoretical calculations of the solidus-liquidus division from the ProCAST programme.

The viscosity value fluctuations over the temperature range in which the medium tested is in its semi-solid state is likely to have been caused by the occurrence of solids, which are ”encountered” by the spindle during its rotation. Probably the alloy ”core” – continuously under the rotor influence and most remote from the crucible walls – is in a semi-solid state while the alloy part outside it slowly solidifies, thus we can notice some jumps during observations of the viscosity value.

The accuracy as regards temperature measurement is a significant problem during rheological measurements of steels and metallurgical slags. A method has not yet been developed for a direct temperature measurement within a sample for the existing device design. The sample temperature is determined on the basis of the temperature measurement in the furnace and estimated with suitable – previously developed – mathematical equations.

To conclude, it must be emphasised that rheological measurements of liquid steel are among the most difficult measurements of this type: experience has to be obtained in their conducting, as well as interpreting their findings.

4. The heat transfer model

There are three mechanisms of heat transfer in the CC process: conduction, radiation and convection. The development of the heat transfer model in the CC process required determining the boundary conditions for the primary cooling zone and the secondary cooling zone.

In the ProCAST software, the solidifying strand temperature distribution is determined by solutions of the generalized diffusion equation - the Fourier equation, which also describes heat transfer [4,12]:

$$\nabla^T (K\nabla T) + Q = c_p\rho\left(\frac{\partial T}{\partial t} + v^T\nabla T\right) \tag{5}$$

where:

T – temperature, ^{o}C

K – matrix of thermal conductivity distribution function,

Q – heat generation rate, resulting from metal plastic deformation or phase transformations occurring in the material,

ρ– metal density at a temperature T, kg/m^3

c_p – specific heat at this temperature, J/kg K

v – velocity vector, m/s.

The boundary conditions declared during the formation of the numerical model of the steel continuous casting process must meet equation 6. The areas where the boundary conditions had been implemented were divided into the primary cooling zone (the outer mould side and the contact strand – mould), and the secondary cooling zone (divided into seven spraying zones). Additionally, a boundary condition was imposed in the form of a definition of the temperature value on the liquid steel meniscus surface in the mould.

In the ProCAST software the boundary conditions may be implemented in three ways. The heat flux may be defined in the software directly as the Flux value (the Neuman condition). This is with the convection (h – substitute heat-transfer coefficient) and the radiation model (ε – emissivity) for heat transfer by radiation. The program allows calculations to be made with all three methods together or using any selected condition. It is described by the equation [1,9]:

$$Q = Flux + h(T - T_a) + \sigma\varepsilon(T^4 - T_a^4) \tag{6}$$

In the presented model, the following set of parameters was adopted as regards the description of the cooling conditions in the CC process:

1) The primary cooling zone

h_I = 18000W/m^{2}K (for the outer mould insert, corresponding to the heat abstraction by water flowing in the mould channels)

h_{II} for the contact surface between the strand and the mould in the form of a temperature function. The values from the range between 832 W/m^2 K and 2000 W/m^2 K were determined.

The value of 1550°C was assigned as the temperature of the steel meniscus in the mould.

2) The secondary cooling zone

Depending on the water flow through the cooling nozzles in a given sub-zone, the following set of heat transfer coefficients was assumed:

Area 1: 900 mm – 1095 mm, h=800 W/m^{2}K

Area 2: 1095mm – 2930mm, h=770W/m^{2}K

Area 3: 2930mm – 6617mm, h=320W/m^{2}K

Area 4: 6617mm – 10768mm, h=290W/m^{2}K

Area 5: 10768mm – 14926mm, h=276W/m^{2}K

Area 6: 14926mm – 18271mm, h=150W/m^{2}K

Area 7: 18271mm – 23300mm, h=110W/m^{2}K

5. Variants assumed for calculations

A model of a mould was developed with the ProCAST software package, with a height of 900 mm and a wall thickness of 40 mm, along with a strand with a height of 23 m and a radius of 10.5 m,.The level of mould filling for all analysed cases and steel grades was 850 mm.

The analysis covered the solidifying strand temperature distribution that was calculated on the basis of three characteristics of the viscosity value for two steel grades. The base model takes into account the viscosity values which were determined on the basis of the chemical composition of the S235 and F320 grade, with a thermodynamic database. The viscosity values for the base model are presented in Figs. 3 and 4 in section 2. However, two sets of viscosity values for each steel grade were developed on the basis of measurements. The former contains the minimum viscosity values, whereas the latter contains the maximum. All viscosity values for the said variants were measured for the same temperature values. Fig. 9 presents the measured values of viscosity as a function of temperature for the S235 steel, whereas Fig. 10 presents the measured values for the F320 steel.

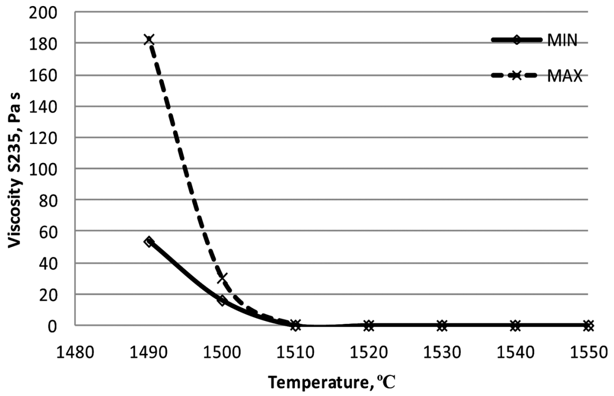

Fig. 9. Viscosity versus temperature for the S235 steel – the minimum and maximum values

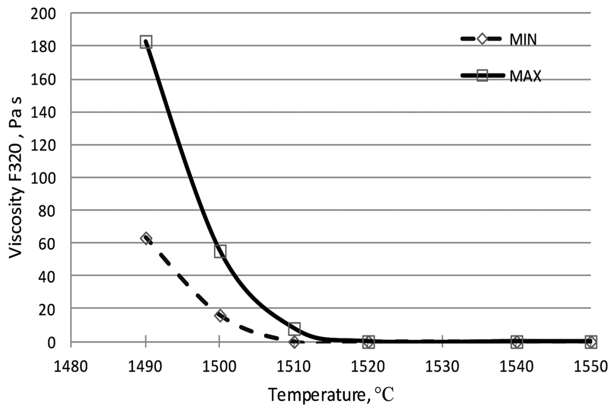

Fig. 10. Viscosity versus temperature for the F320 steel – the minimum and maximum value

6. Calculation results

On the basis of the developed material-related parameter sets discussed in section 2 and 5, a series of numerical simulations were performed for the two examined steel grades – S235 and F320.

The influence of viscosity values on the solidifying CC strand temperature distribution was examined.

For all variants, the shell thickness was also examined after leaving the mould and the metallurgical length that had been calculated from the liquid steel meniscus in the mould to the total solidification of the cast strand were compared. The measured values of the shell thickness, along with the metallurgical lengths, are presented in Table 3.

For the F320 steel grade, in which the viscosity values were determined with the ProCAST software, the shell with a thickness of 2.21 cm and the metallurgical length of 10.9m were obtained. For the two variants where the viscosity values were obtained from the author's own research, the values of the shell thicknesses and the metallurgical lengths were very similar. The smallest shell thickness under the mould of 2.19 cm was received for variant 1, which was based on the minimum viscosity values. It was in this case that the most substantial metallurgical length was obtained, and it was 11 m.

However, for the S235 steel grade, the shell thicknesses and the metallurgical lengths have the same values, both for the viscosity values determined with the ProCAST software, and for the minimum values measured during the tests. In the ProCAST model and for variant 1, the shell thickness of 2.2 cm and the metallurgical length of 12.6 m were obtained. A slight difference was visible for variant 2 when the maximum viscosity values recorded during the measurements were considered.

TABLE 3
The metallurgical length and the shell thickness calculated for three calculation variants

Calculation variants	**Metallurgical length [m]**	**The shell thickness under the mould [cm]**
ProCAST model - S235	12.6	2.2
Variant 1 - S235	12.6	2.2
Variant 2 - S235	12.4	2.21
ProCAST model - F320	10.9	2.21
Variant 1 - F320	11	2.19
Variant 2 - F320	10.8	2.2

The curves showing the calculated temperature distribution for the individual variants followed the same pattern. Differences could only be observed in the primary cooling zone. Figs. 11 and 12 show the temperature distribution for the base model and for variant 2, with the maximum viscosity values from the measurements for the two steel grades tested.

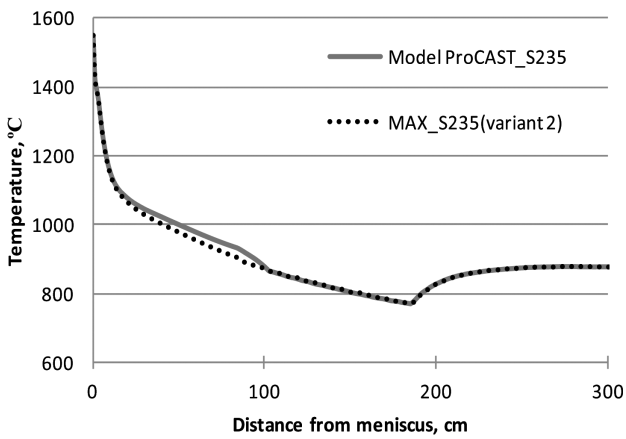

Fig. 11. The temperature distribution for variant 2 and the base model for the S235 steel

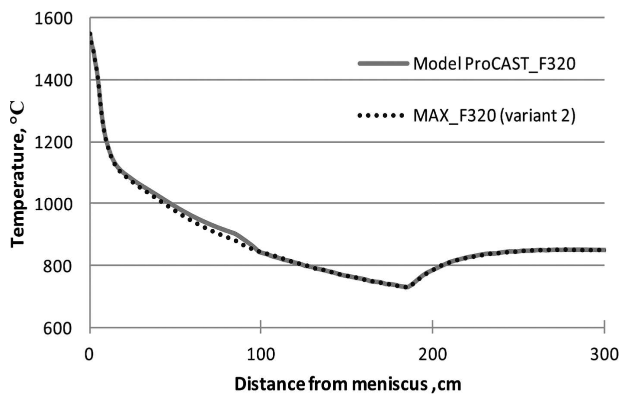

Fig. 12. The temperature distribution for variant 2 and the base model for the F320 steel

The calculated values of temperature for all variants were similar. The biggest difference in the temperature distribution was observed for the base model and variant 2, which was 8°C. For variants 1-3, based on viscosity values from tests, a difference in temperature of 1-4°C was observed.

7. Conclusions

The paper presents the influence of viscosity values on the solidifying CC strand temperature distribution for two steel grades: S235 and F320. The numerical calculations were made with the ProCAST software package. Three models were developed and compared for two steel grades: in these models, viscosity values as a function of temperature were changed. The models based on the data measured during the author's own research were compared to the base model, where the viscosity was determined on the basis of chemical composition of F320 and S235 steels with the CompuTherm LLC thermodynamic database.

The numerical models of the steel continuous casting process that were developed with the ProCAST software correctly and stably responded to changes in the material-related parameters – including a change in viscosity.

The numerical models allowed analyses to be conducted, which covered the examination of the influence of viscosity changes on the solidifying strand temperature distribution. The analysis was carried out on the basis of additional process parameters, i.e. the shell thickness, the metallurgical length.

On the basis of the obtained simulation results, it was found that applying the viscosity values coming from the author's own research had no significant impact on the solidifying strand temperature distribution. The temperature difference for the models tested was at most, 8°C, and was observed only in the primary cooling zone.

In the numerical modelling of the steel continuous casting process, the viscosity values that were calculated on the basis of Newton's law, do not have a significant influence on the solidification process on the whole strand length. The authors observed that the numerical model showed sensitivity at its highest to a change in the viscosity value in the primary cooling zone, which is in line with the process theory, as steel exists both in the liquid and in the semi-solid state in this zone.

In the future the authors plan to extend their research by the use of other non-Newtonian rheological models for modelling of the continuous steel casting process (in particular in the primary cooling zone). To this end suitable rheological measurements should be conducted so that the range of the shear rates applied is as broad as possible (while maintaining a laminar flow), so that it would be possible to obtain material-related data for the selected non-Newtonian model.

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REFERENCES

[1] M. Knap, J. Falkus, A. Rozman, J. Lamut, The prediction of hardenability using neuronal networks, Archives of Metallurgy and Materials **53**, 761-766 (2008).
[2] L. Madej, H. Paul, L. Trębacz, L.W. Wajda, M. Pietrzyk, Multi billet extrusion technology for manufacturing bi-layered components, CIRP Annals - Manufacturing Technology **61**, 235-238 (2012).
[3] J. Falkus, L. Trębacz, B. Zawada, Utilization of the steelmaking slag by reduction with the use of the modified the chemical composition of the input material, Archives of Metallurgy and Materials **55**, 1105-1112 (2010).
[4] M. Rywotycki, K. Miłkowska-Piszczek, L. Trębacz, Identification of the boundary conditions in the continuous casting of steel. Archives of Metallurgy and Materials **57**, 385-393 (2012).
[5] B.G. Thomas, Modeling of the continuous casting of steel – past, present and future. Metallurgical Transactions **33B**, 12, 795-812 (2002).
[6] B. Mochnacki, Zastosowanie metod numerycznych w obliczeniach cieplnych procesu ciągłego odlewania stali. Archiwum Hutnictwa **28**, 1, 79-88 (1983).
[7] A. Burbelko, J. Falkus, W. Kapturkiewicz, K. Sołek, P. Drożdż, M. Wróbel, Modeling of the grain structure in the steel continuous ingot by CAFE method, Archives of metallurgy and materials **57**, 379-384 (2012).
[8] L. Sowa, A. Bokota, Numerical model of thermal and flow phenomena the process growing of the CC slab. Archives of metallurgy and materials **56**, 359-366 (2011).
[9] A. Cwudziński, Numerical simulation of liquid steel flow and behaviour of non-metalic inclusions in one-strand slab tundish with subflux turbulence controller and gas permeable barrier, Ironmaking and Steelmaking **37**, 3, 169-180 (2010).
[10] K. Miłkowska-Piszczek, M. Dziarmagowski, A. Buczek, J. Pióro, The methods of calculating the solidifying strand shell thickness in a continuous casting machine. Archives of Materials Science and Engineering **57**, 2, 75-79 (2012).
[11] A. Cwudziński, Numerical simulation of behavior a non-metalic inclusions in an one-strand slab tundish with steel flow control devices, Archives of metallurgy and materials **56**, 611-618 (2011).
[12] ProCAST – User Manual.
[13] D. Mazumdar, J.W. Evans, Modeling of steelmaking process. CRC Press 2010.
[14] J. Ferguson, Z. Kembłowski, Reologia stosowana płynów, Wydawnictwo MARCUS, Łódź 1995.
[15] P. Migas, M. Korolczuk-Hejnak, M. Karbownicz ek, Rheological measurements of selected grades of liquid steels; Rheology – theory and application **2** EKMA, 191-202 Warszawa 2011.
[16] M. Korolczuk-Hejnak, P. Migas, Selected grades of steel as rheologically defined liquid bodies, Archives of Metallurgy and Materials **57**, 2, 583-591 (2012).
[17] M. Korolczuk-Hejnak, P. Migas, Analysis of selected liquid steel viscosity, Archives of Metallurgy and Materials **57**, 4, (2012).
[18] K. Sołek, M. Korolczuk-Hejnak, M. Karbowniczek, An analysis of steel viscosity in the solidification tem-

perature range, Archives of Metallurgy and Materials **56**, 3, 593-598 (2011).
[19] K. Sołek, M. Korolczuk-Hejnak, W. Ślęzak, Viscosity measurements for modeling of continuous steel casting, Archives of Metallurgy and Materials **57**, 1, , 333-338 (2012).
[20] T.G. Mezger, The rheology handbook. For users of rotational and oscillatory rheometers. 2nd revised edition, Vincentz Network, Hannover, 172-175 (2006).

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