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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K. SOŁEK*, M. KOROLCZUK-HEJNAK*, W. ŚLĘZAK*

VISCOSITY MEASUREMENTS FOR MODELING OF CONTINUOUS STEEL CASTING

POMIAR LEPKOŚCI STALI DLA MODELOWANIA PROCESU CIĄGŁEGO ODLEWANIA STALI

This paper presents the results of the rheological analysis of five chosen grades of steel: F320, UG-m, S235-c, ETZ1, B500SP. These steels are produced in industrial conditions and used for slabs and billets.

In a metallurgical processes the viscosity parameter is an important indicator characterizing the behavior of liquid metal in the industrial aggregates. Due to the difficulty of the experiments only a small number of high temperature viscosity measurements are performed.

Rheological analysis of selected iron solutions was conducted in the range of liquid and below-liquid point. Measurements were taken using a high temperature viscometer FRS1600 working in accordance with the concentric cylinder method.

The acquired rheological characteristic allow to conclude that the investigated steels properties depend on the shear rate and temperature. The results will be used for numerical modeling of the steel casting process.

Keywords: rheology; viscosity; rheometer; steel casting process

W pracy przedstawiono analizę lepkości pięciu wybranych gatunków stali: F320, UG-m, S235-c, ETZ1, B500SP. Powyższe gatunki stali są wytwarzane w warunkach przemysłowych i stosowane na wyroby płaskie oraz długie.

W procesach metalurgicznych wartość współczynnika lepkości jest ważnym wskaźnikiem charakteryzującym zachowanie ciekłego metalu w agregatach przemysłowych. Ze względu na skalę trudności wykonuje się niewiele wysokotemperaturowych pomiarów lepkości.

Analizę reologiczną wybranych stopów żelaza przeprowadzono w zakresie temperatur likwidus oraz poniżej punktu likwidus. Pomiar lepkości zostałprzeprowadzony na reometrze wysokotemperaturowym FRS1600. Do pomiarów wykorzystano metodę osiowo- koncentrycznych cylindrów.

W ramach pracy wykonano charakterystyki reologiczne, które pozwalają stwierdzić, że analizowane stale wykazują zależności od szybkości ścinania oraz temperatury. Wyniki uzyskane z pomiarów reologicznych zostaną wykorzystane do numerycznego modelowania procesu ciągłego odlewania stali.

1. Introduction

Mathematical modeling and control of molten metal processing operations require the knowledge of the thermo-physical properties of liquid metals at their melting-points. Mass, momentum and energy transport processes in liquid metals will be well understood if thermo-physical parameters such as density, surface tension, viscosity, diffusivity and thermal conductivity are measured precisely. The accurate measurement of these properties is the key prerequisite to advancement in the development of engineering procedures.

Viscosity is a rheological property of materials which presents itself when the velocity gradient between different layers of material is observed. Viscosity is an important rheological parameter for understanding the hydrodynamics and kinetics of reactions in metal casting.

Most theoretical predictions of transport coefficients of liquid metals are based on the mechano-statistical theory of liquids which assumes that pair interactions are the primary interaction forces and are sufficient to describe the energy exchanges between liquid atoms. Majority of the existing models are of theoretical nature and have previously been used mainly to calculate the viscosity of low-melting metals like aluminum, zinc, lead, tin, cooper and antimony. Furthermore due to the dif-

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, DEPARTMENT OF FERROUS METALLURGY, FACULTY OF METALS ENGINEERING AND INDUSTRIAL COMPUTER SCIENCE, 30-059 KRAKÓW, 30 MICKIEWICZA AV., POLAND

ficulty of the experiments only small number of high temperature viscosity measurements is performed.

Authors of [1] conducted the rheological analysis of tool steel X210CrW12 using a rotational rheometer with a large value of shear rate (up to $250s^{-1}$). Changes were observed in the viscosity of steel depending on the amount of liquid and solid phases in the sample.

Authors of this paper focus (in this and in the past researches [2,3,4]) on iron solutions in the range of liquid and semi-solid temperature for different chemical compositions but for much lower values of shear rate. The value of temperature and shear rate applied were based on real metallurgical processes, in this case on the steel continuous casting process.

2. Experimental setup

The high temperature rheometer FRS1600 which was used for the rheological analysis was designed as a result of cooperation of the Anton Paar Company and the Faculty of Metals Engineering and Industrial Computer Science at the AGH University of Science and Technology. The used apparatus is a prototype and it is still under construction. Basically it consists of the head and the furnace which allows obtaining the temperature in the range 400-1532°C.

Rotational rheometer FRS1600 has a concentric cylinder measuring system (Figure 1) working in accordance with the Searle's method (1912) [5, 6, 7]. The experiments were performed in a large rheological gap conditions, inner diameter of the cup and diameter of the bob had accordingly: 30mm (R_o = 15mm) and 15mm (R_i = 7.5mm) (Figure 1). Concentric means that both cylinder-shaped components have the same symmetry axis which is also the rotation axis. In this case the bob is set in motion and the cup is stationary (Searle's method). Nearly all rheometers used in industrial laboratories work using this principle.

The main advantage of the rotational technique is that the viscosity can be measured at different fixed values of the shear rate. This feature makes it possible to analyze the non-Newtonian behavior of partially solidified metals and alloys.

As a part of this project authors designed the geometry for the measurement system used to measure the viscosity: cup-bob, using ceramic materials made of Al_2O_3+ 5% ZrO_2 (Figure 2). Perforations on the walls of the spindle and crucible were specially crafted to prevent slippage of the medium on the surface of the rotating rod.

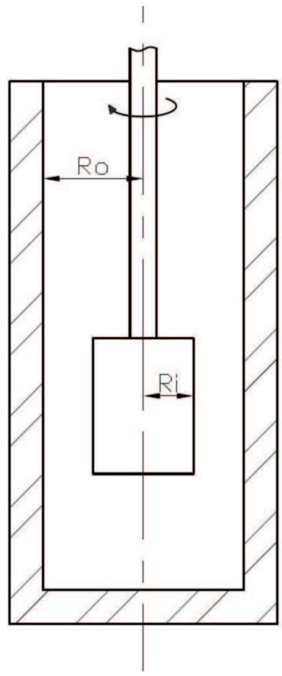

Fig. 1. Concentric cylinder measuring system

3. Experimental procedure

The main aim of this paper is the development of material characteristics in terms of numerical modeling of the steel casting process. Viscosity measurements were conducted for five selected grades of steel: UG-m, F320, S235-c, ETZ1, B500SP using different values of the rheological parameters. The used types of steel are produced in industrial conditions and are used for slabs and billets. The measurements were performed in the temperature range of 1400 to 1530°C, depending on the grade of steel. Chemical composition of steel is shown in Table 1.

TABLE 1
Chemical composition of investigated steel [%]

C	Mn	Si	P	S	Cu
UG-m					
0.049	0.213	0.007	0.011	0.009	0.031
F320					
0.097	0.736	0.018	0.013	0.011	0.022
S235-c					
0.083	0.524	<0.005	0.016	0.014	0.032
ETZ1					
0.096	0.671	3.810	0.014	0.038	0.195
B500SP					
0.253	0.792	0.171	0.019	0.030	0.235

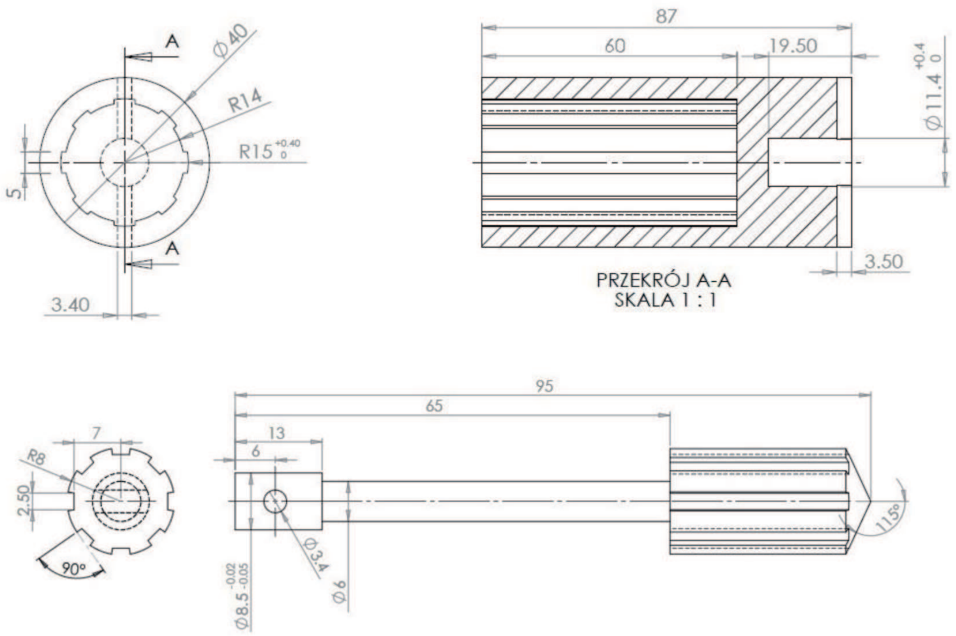

Fig. 2. Geometry of measuring system

The liquid point for each steel was calculated using Loessera and Wansela tables – commonly used in the industry. The liquidus temperature for the investigated steel was:

- 1530°C for UG-m,
- 1527°C for F320,
- 1525°C for S235-c,
- 1506°C for ETZ1,
- 1508°C for B500SP.

4. Modeling the viscosity of metal alloys in a semi-solid state

The viscosity measurements were conducted as temperature and shear rate functions. The viscosity of semi-solid metal alloys is sensitive to both of these parameters. The measurements were performed in temperature range of 1400 to 1530°C, depending on the grade of steel.

The following Figures (3-14) present selected results of the rheological measurements. Figures (3, 4, 7, 9, 11, 13), which display the relation between temperature and viscosity, contain two types of curves: the measured values (white points) and statistically estimated model (black dots). Value of the shear rate ranged from 0.1 to 20 s^{-1} in each of the investigated temperatures, which is the direct reason of the peek viscosity values occurrence on the charts. The viscosity as a function of shear rate depending on the temperature values are presented in (5, 6, 8, 10, 12, 14).

Each rheological measurement began at temperatures close to liquidus temperature (previously calculated for every iron solution). Next the studied samples were cooled at a rate of 1 degree per minute, until rapid changes of viscosity occurred. After that the viscosity measurements were carried out with greater frequency: every one degree (UG-m, F320) (Fig. 4), every two degrees (S235-c steel) and every five degrees (ETZ1, B500SP).

Figures 3-6 present the viscosity value depending on changes of temperature for different values of shear rate for UG-m steel. The temperature during the experiments was lowered from 1530 to 1480°C.

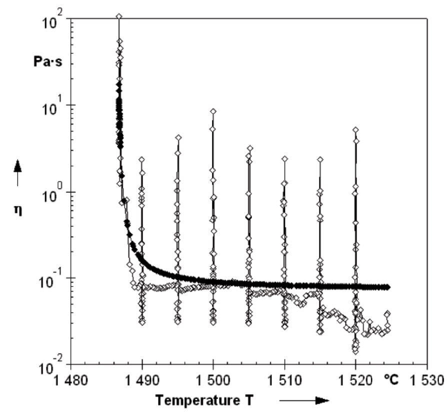

Fig. 3. Viscosity changes vs. temperature

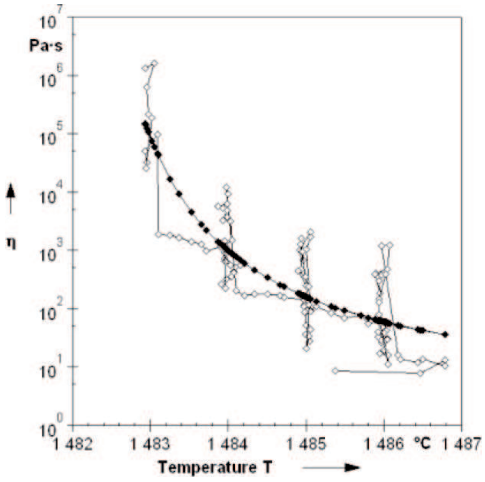

Fig. 4. Viscosity changes vs. temperature

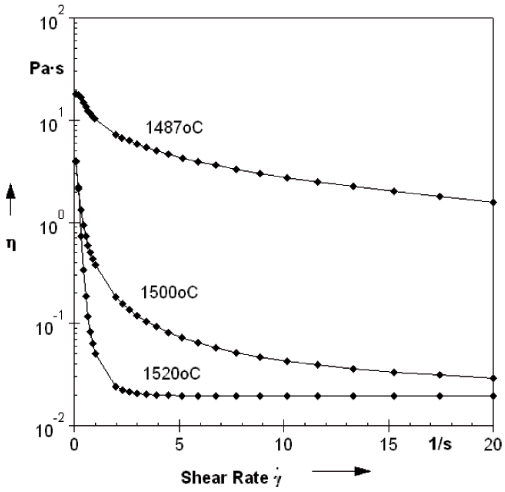

Fig. 5. Viscosity curves vs. shear rate for temperatures 1487, 1500 and 1520°C

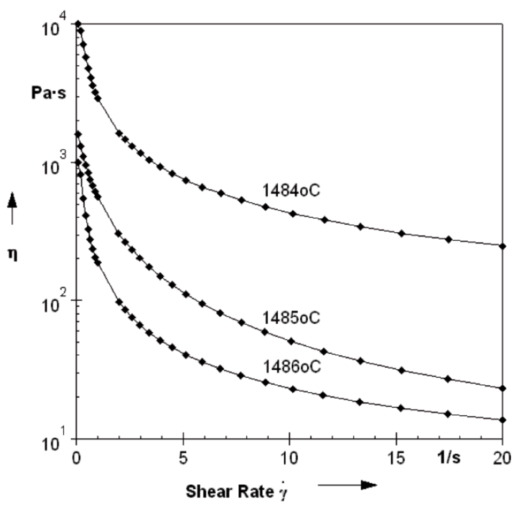

Fig. 6. Viscosity curves vs. shear rate for temperatures 1484, 1485 and 1486°C

In pictures 7-8, the results of the measurements for F320 steel were shown. In this case temperature was changed from 1520 to 1480°C. Value of shear rate was changed from 0.1 to 20 s^{-1}.

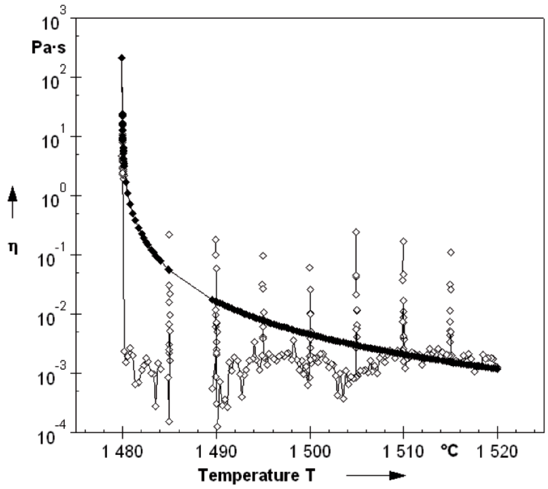

Fig. 7. Viscosity changes vs. temperature

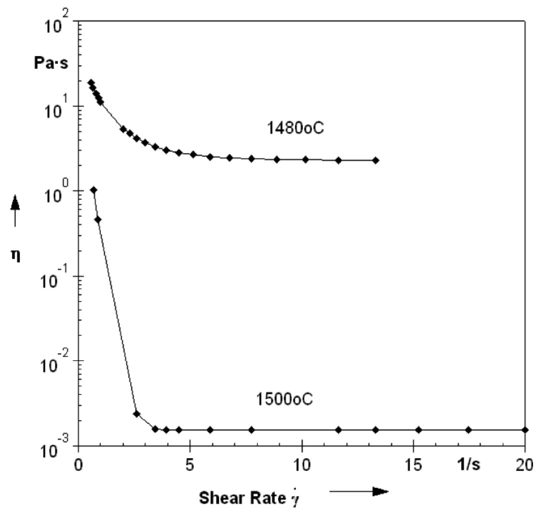

Fig. 8. Viscosity changes vs. shear rate for temperatures 1480 and 1500°C

Figures 9-10 show the relations of viscosity, temperature and shear stress for S235-c steel.

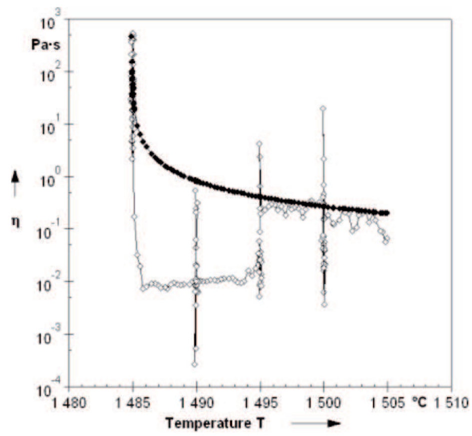

Fig. 9. Viscosity changes vs. temperature

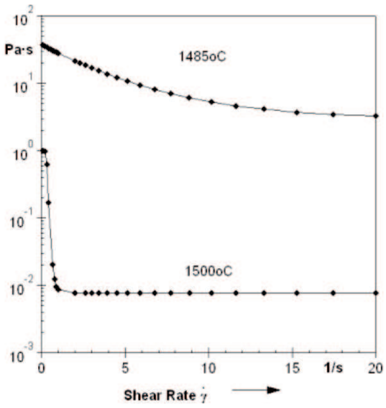

Fig. 10. Viscosity changes vs. shear rate for temperatures 1485 and 1500°C

Figures 11-12 present the influence of temperature and shear rate changes on the viscosity value for ETZ1 steel.

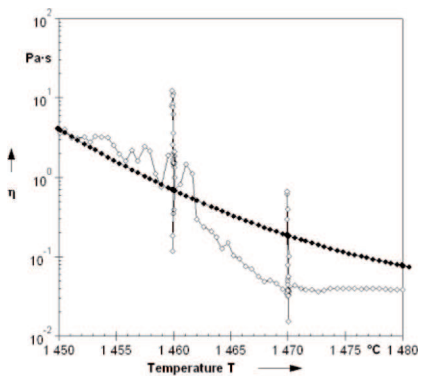

Fig. 11. Viscosity changes vs. temperature

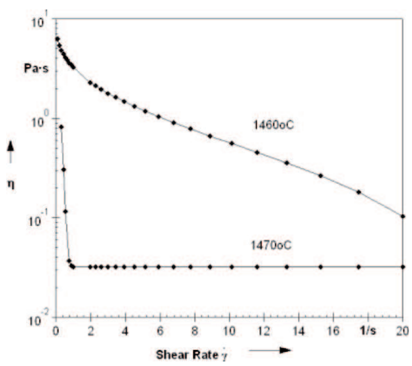

Fig. 12. Viscosity changes vs. shear rate for temperatures 1460 and 1470°C

Figures 13-14 show the results of the measurements for B500SP steel. In this case the temperature was altered in the range of 1475-1450°C.

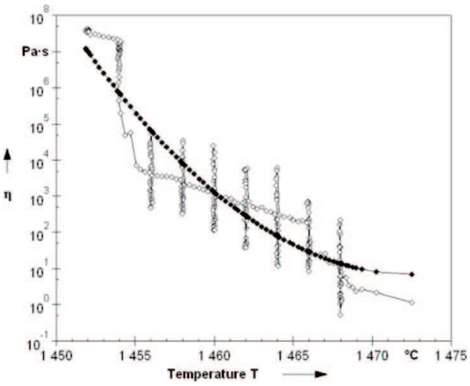

Fig. 13. Viscosity changes vs. temperature

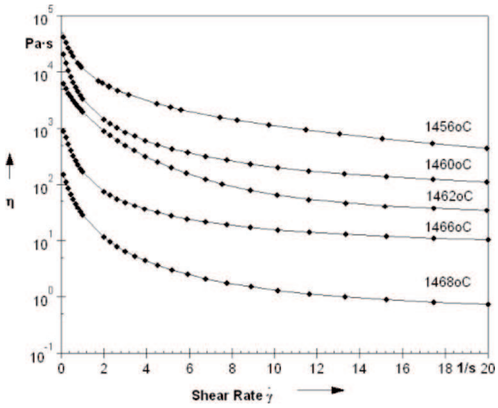

Fig. 14. Viscosity changes vs. shear rate for temperatures 1456, 1460, 1462, 1466 and 1468°C

5. Analysis of the results

For this study, the measurements of the viscosity were conducted using selected ferrous alloys in semi-solid state. Based on the results of the rheological analysis of steel: UG-m, F320, S235-c, ETZ1, B500SP it can be stated that:

- Authors of this paper observed an increase in the sensitivity of the viscosity parameter for shear rate (under the applied measurement conditions).
- It was observed that the impact of shear rate on the viscosity value is lower at temperatures close to the liquidus temperature, which is consistent with [1].
- If the difference between the solidus and liquidus temperatures is small, the measured viscosity value presents a greater variability gradient.
- In existing numerical models viscosity mostly depends on the temperature value. The obtained results could be used to estimate the viscosity parameter as a function of shear rate, since they indicate a strong relation between shear rate and viscosity values.

6. Conclusions

In order to improve the numerical modeling of the continuous steel casting process it is crucial to develop an empirical function of viscosity, temperature, shear rate and chemical composition, due to the fact that most of the existing models are theoretic or semi-empiric, but were developed only for low melting metal alloys. This paper is one the first which describe the issues of high temperature measurements of these rheological parameters for liquid steel. The performed experiments gave results which are interesting from the scientific point of view; therefore the authors plan to continue the rheological analysis of steel.

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