Determination of the liquid steel viscosity curves using a high temperature rheometer

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Abstract. Rheological measurements of high melting temperature materials require specialist equipment, which allow to obtain high temperature inside. This situation take place in case of iron alloys. In literature there is lack of information about rheological properties of liquid iron solutions. This paper is intended to supplement the data in this regard; included in the study of iron solutions rheological properties: five chemical composition with carbon amount in the range between 0.39 – 0.89 %, while used shear rate in the range between 40 -180 s⁻¹. Obtained viscosity values are set in the range between 0.002 -0.018 Pa∙s. The obtained results could be used for verification of the model which calculate the parameters of liquid iron alloys during casting, in which the viscosity is one of the mane parameter.

1. Introduction

Rheology is a branch of science that has evolved from a branch of physics. Today, however, it is an independent area of knowledge that dates back over 70 years. The rheological behaviour of a material is described by the relationships between stresses, strains, strain rates, and the time in which the material has been subjected to such a strain. Such relationships are called rheological equations of state of the material, or for short - rheological equations [1]. The main task of rheology is to develop models to describe the 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 relationships between the stress, strain, strain rate and the stress growth rate (rheological function [2]). However, it should be emphasised that the following rheological equations of state (1-3) describe idealised bodies - ideal bodies that do not exist in reality. The concept of the ideal body simplifies theoretical considerations and enables mathematical methods to be applied to analyse any interesting phenomena. Ideal bodies are only extreme cases to which real bodies resemble to a lesser or higher degree. In specific conditions rheological properties of real bodies are approximated by mathematical rheological models; these are combinations of three basic rheological models of ideal bodies, such as [3]:

Hooke ideal elastic body,
St. Venant ideal plastic body,
Newtonian ideal viscous fluid.

Rheological tests of materials characterised by high melting temperatures require specialist equipment; these enable samples to be heated to high temperatures. This is the case for, among others, ferrous alloys: however, subject literature is short of data containing information on rheological
properties of liquid ferrous solutions. This study aims to supplement data in this area. It contains rheological tests of ferrous solutions, that is, five chemical compositions at applied shear rates from 40 to 180 s\(^{-1}\). The obtained values of dynamic viscosity coefficient are within the range of 0.002 - 0.018 Pa s. These results may be useful for the verification of models for calculating the parameters of liquid ferrous alloys, e.g. during the casting of steel, where viscosity is one of the basic parameters.

In his study [4] S. Sridhar emphasised the difficulties as regards access to high-temperature, thermophysical data that is needed for computer process modelling and for the understanding and developing processes from the point of science and technology, along with improving process control and product quality. Generating reliable measurements of physical properties of materials is time consuming and requires substantial experimental knowledge. In industrial conditions experimental data is often needed very quickly in order to verify and optimise a specific process. Therefore, there is substantial demand for mathematical models that describe the physical and thermophysical material parameters in their solid, liquid and semi-solid states.

Viscosity is a measure of "friction existing in a fluid", or "resistance" that occurs in liquid or gas during flow. It 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 like this occurs at low velocities [2]. The viscosity effect in metallurgical processes is amongst the most important of effects. It influences the behaviour of reacting phases (metallic, slag and gaseous) with regard to the kinetics of mass exchange or chemical reactions [5]. Viscosity plays a significant role in all metallurgical processes - ironmaking, steelmaking, ladle refining, steel casting, and processes related to solidification [6,7]. It is very important from the standpoint of flow of liquid phases that are continuously moving during those processes, as well as due to the internal structure of the metallic or slag phase and related possibilities of contamination absorption, or even the ability to deform in their semi-solid states [8, 9, 10, 11, 12].

Issues of viscosity and rheological properties of liquid ferrous solutions are important from the perspective of modelling, and also the control of actual production processes related to the manufacturing of metals, including iron and steel. Conducted analysis within subject literature indicates that there are many theoretical considerations concerning the effect of viscosity of liquid metal solutions. The vast majority of models constitute a group of theoretical or semi-empirical equations, where thermodynamic parameters of solutions, or some parameters determined by experimental methods, are used for calculations of the dynamic viscosity coefficient.

2. Research on Liquid Ferrous Solutions

Figure 1 presents a schematic diagram of a high-temperature rheometer as used for rheological tests of liquid metals and slags [13, 14, 15, 16].

![Figure 1. Scheme presenting a high-temperature rheometer FRS1600](image)

The main part of the FRS1600 rheometer is its head, along with its cooling system. The head, like the furnace, is computer controlled. A thermocouple for temperature measurement is placed in the
furnace, and the tubular resistance furnace with a mullite tube is controlled by a Eurotherm controller. An inert gas - argon with purity of 5.0 - is fed into the furnace tube to enable a protective atmosphere to be maintained during rheological measurements that last several hours. Figure 3 presents measurement tools used for rheometric tests.

Figure 2. Measuring systems

In this study, the measurement methodology in a system of coaxial Searle type cylinders was used for conducting high-temperature rheometric tests of steel. The cylindrical measurement method is based on a system consisting of an inner cylinder (bob) and an outer cylinder (cup). In the study, the following ferrous solutions were examined.

| Steel grade | C    | Mn   | Si   | Cr   | Ni   | Mo   | V   |
|-------------|------|------|------|------|------|------|-----|
| 90CrV6      | 0.89 | 0.26 | 0.19 | 1.43 | 0.44 | 0.06 | 0.106 |
| 34CrNiMo    | 0.39 | 0.62 | 0.24 | 1.57 | 1.67 | 0.26 | 0.074 |
| DHQ3        | 0.80 | 0.26 | 0.69 | 2.93 | 0.13 | 0.54 | 0.011 |
| 42CrMo4     | 0.43 | 0.83 | 0.23 | 1.13 | 0.29 | 0.28 | 0.0068 |
| 45          | 0.46 | 0.74 | 0.30 | 0.17 | 0.24 | 0.06 | 0.052 |

For each of the above grades the values of solidus and liquidus temperatures of the above solutions (Table 2) [16] were calculated with the CompuTherm LLC thermodynamic databases, supplied together with the ProCast software package. The calculated temperature values are necessary to determine the measurement pattern, assuming that the steel tested is to be in the fully liquid state.

| Gatunek stali | Temperatura likwidus [ºC] | Temperatura solidus [ºC] |
|---------------|---------------------------|--------------------------|
| 90CrV6        | 1463                      | 1349                     |
| 34CrNiMo      | 1465                      | 1343                     |
| DHQ3          | 1461                      | 1345                     |
| 42CrMo4       | 1492                      | 1422                     |
| 45            | 1493                      | 1418                     |
The rheological tests were conducted for five steel grades with different chemical compositions (Table 1). The tests were carried out at their liquidus temperatures (Table 2) and at temperatures up to 20 Celsius above and below the calculated liquidus temperatures. The measurements were taken every 10 degrees.

Figure 3 present the flow curves of five steel grades differing with chemical compositions. The objective of this presentation of results is to picture the differences between the values of dynamic viscosity coefficient and tangential shear for a given chemical composition at various temperatures.

![Figure 3. Viscosity curves for different steel grades](image-url)
Based on the analysis of the above graphs (Fig. 50-54) it was found that the dynamic viscosity coefficient values range from 0.014 to 0.003; in addition for the 90CrV6 steel, the top value of its dynamic viscosity coefficient achieves 0.018 Pa s, and for 42CrMo4 the bottom value is 0.003 Pa s. In addition, it was observed that when the chromium and molybdenum content increases, the range of viscosity values extends. It is particularly visible for 34CrNiMo, which contains relatively high amounts of chromium and molybdenum, and has the highest content of nickel out of the steel grades tested. However, some differences in the top values of viscosity coefficient at various temperatures in the DHQ3 steel may be observed. This particular steel is characterised by the highest chromium and molybdenum content out of those steels analysed, and it has a relatively high carbon and low nickel content in its chemical composition. Therefore we can suppose that it is just the chromium and molybdenum content that creates favourable conditions for extending the range of dynamic viscosity coefficient of liquid steel. It was also observed that when the manganese content increases in the chemical composition of a ferrous solution, the range of the dynamic viscosity coefficient values contracts. 42CrMo4 has the highest manganese content, and for this steel the viscosity curves plotted for various temperatures virtually coincide.

3. Conclusion

The problem of viscosity and rheological properties of liquid ferrous solutions is important from the perspective of modelling, and also control of the actual production processes related to manufacturing of metals, including iron and steel. The conducted analysis of literature indicates that there are many theoretical considerations concerning rheological effects, while experimental results are scarce.

In this study, the measurement methodology in a system of coaxial Searle type cylinders was used for conducting high-temperature rheometric measurements of steel. During preparations for the tests, the shapes of measurement tools were designed, and tools made of various ceramic materials were tested. In terms of availability and strength, the optimal material for the measurement systems was selected.

Rheological tests of liquid steel solutions were then carried out, and five various chemical compositions were analysed. During these experiments the solution temperature was step changed every 10°C, from 20°C above the calculated liquidus temperature to 20°C below this temperature. In addition, during measurements the shear rate value was changed from 40 to 180 s⁻¹. During these measurements, the time in which the sample tested was subjected to the same force was also modified. Finally, it was revealed that time was a rheological parameter, and which for measurements of liquid ferrous solutions (in constant process conditions), did not change the rheological nature of the medium examined.

As a result of these conducted experiments the values of liquid steel viscosity coefficient were obtained. These ranged from 0.002 to 0.018 Pa s.

For systems in their fully liquid state (at the theoretical liquidus temperature and above), the conducted rheological analysis allows us to understand that the liquid steel behaves like a Newtonian liquid, albeit with some departures within the tested range of shear rate which may be related - among others - to the occurrence of disturbances to laminar flow in the sample.

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