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Rheological Properties of Typical Ceramic Slurries Used in the Lost Wax Technology

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Abstract

The results of investigations of the rheological properties of typical ceramic slurries used in the investment casting technology – the lost wax technology are presented in the paper. Flow curves in the wide range of shear velocity were made. Moreover, viscosity of ceramic slurries depending on shearing stresses was specified. Tests were performed under conditions of three different temperatures 25, 30 and 35°C, which are typical and important in the viewpoint of making ceramic slurries in the investment casting technology.
In the light of the performed investigations can be said that the belonging in group of Newtonian or Non – Newtonian fluid is dependent on content of solid phase (addition of aluminum oxide) in the whole composition of liquid ceramic slurries.

Keywords: Rheological properties, Non – Newtonian fluid, Ceramic slurries.

1. Introduction

The need of performing rheological investigations concerning the disperse systems with non-Newtonian continuous phase, it means ceramic slurries and binders used in the investment casting technology, is obvious, due to constant variations of the applied materials.

The features required from ceramic moulds produced by the investment casting technology are listed below:

- homogeneity of compositions and a high stability of physicochemical parameters in the determined time,
- good wettability of organic surfaces (wax or polymer patterns),
- no reactivity with materials of patterns,
- the proper microstructure, facilitating the effective evaporation of the solvent phase (shortening of drying times of moulds),
- adequately high mechanical strength and a lack of deformability,
- resistance to a high temperature influence during annealing and moulds pouring,
- a lack of reactivity with metal material during moulds pouring and their cooling.

In order to obtain good quality moulds and - in consequence - good quality castings, rheological properties of the applied materials should be recognised.

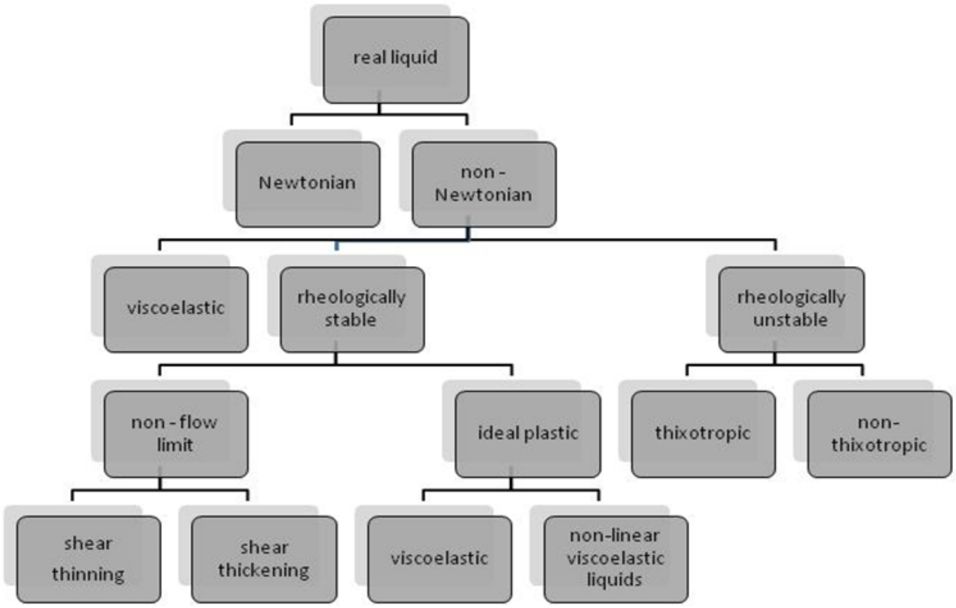

Fig. 1. Classification of fluids on account of their rheological behaviour [2]

2. Rheology

Rheology is defined as a knowledge of flowing and deformations of all forms of matter under an influence of stresses [1]. Fluids behaviour in dependence of external stresses, it means in dependence of deformations occurring in material subjected to strains, can be divided in a way shown in Fig 1.

Real fluids are usually divided into two basis groups [2- 4]:

- Newtonian fluids – subordinated to the law stating that tangent stresses in fluids are directly proportional to the shear rate, thus their dynamic viscosity is constant and independent of the shear rate,
- Non-Newtonian fluids – in which viscosity is not a constant value, but depends on several factors, among others on a temperature, shear rate or mixing time.

Ceramic slurries as well as binders applied in the investment casting technology, in dependence of their viscosity belong either to the Newtonian or non-Newtonian fluids [5, 6]. In order to determine rheological properties of non-Newtonian fluids a larger number of characterizing parameters is needed, than in case of the Newtonian fluids. What is more, a character of the dependence between shear rates and tangent stresses is not linear and additionally is shifted along the axis of ordinates in relation to the Newtonian fluids [7].

The temperature seems to be a very essential parameter, taken into account in the technological process of producing moulds by the investment casting method. It significantly influences the fluid viscosity value, that is also - indirectly - the ceramic moulds quality.

Viscosity itself is the kinetic value correlated with transferring of the momentum, which is transferred in fluids thus of intermolecular forces inhibiting their movements [8]. The temperature dependence of viscosity in fluids was determined by J. Guzman in the equation called the Guzman – Arrhenius equation [9]:

$$\eta = A * e^{\frac{\Delta E_\eta}{RT}} \qquad (1)$$

where:
η – viscosity [P],
A – reaction rate constant [-],
R – universal gas constant [J/(mol·K)],
T – temperature [K],
ΔEη – activation energy [kcal/mol].

3. Methodology of investigations

Investigations of rheological properties of the ceramic slurries 1 and 2 applied in the investment casting technology were divided into two stages:

- I – measurements of conventional viscosity by means of the Ford's cup in temperature of 25°C.
- II – investigations of flowing and dynamic viscosity with using the rotational viscosimeter Rheotest 2 and with considering various temperatures: 25, 30 and 35°C.

Stage I

The Ford's cup is the device used for relative measurements and the viscosity classification.

The measurement was as follows: the Ford's cup was filled with the tested fluid (ceramic slurry 1 or ceramic slurry 2), then this fluid was freely flowing out through the opening - of a diameter of 4 mm - in the cup bottom and the flowing out time was measured.

The conventional viscosity obtained from the performed measurements was compiled with the diagram of the kinematic viscosity dependence on the flowing out time of the reference fluid from the Ford's cup with the given diameter of the flow out opening (4 mm).

Stage II

The rotational rheometer Rheotest 2 is the device used for investigating characteristics of fluids in a wide range of the shear rates (from 0.2 to 1.3 • 10^{-3}, s^{-1}), of shearing stresses (from 130 to 3 • 10^3, N/m^2) and the dynamic viscosity (from 10 to 10^7, P • s).

Its operation is based on the relation between the dynamic viscosity coefficient η and the moment of tangent forces operating in the fluid layer when it is rotating in between two coaxial cylinders [10].

The measurement was based on the fluid placement in the ring-shaped slots in between two coaxial cylinders of the measuring system. The external cylinder is stable, while the internal one is rotating with the constant angular velocity and is connected with a measuring shaft by means of the calibrated spring. The measurement of the torque value allows to calculate the shearing tensions and fluid dynamic viscosity at the given shear rate. The rheometric measurements of ceramic slurries 1 and 2 were performed at temperatures of 25, 30 and 35°C, respectively.

4. Analysis of the results

The performed investigations concerned rheological properties of liquid ceramic slurries applied in the investment casting technology.

Figure 3 presents the influence of shear rates on shearing stresses for the ceramic slurry 1. This is a suspension of mullite in the water binder Ludox AM. The amount of a solid component added to a binder decides on viscosity of a ceramic slurry. For the ceramic slurry 1 – viscosity, determined by the Ford's cup of an outflow opening diameter 4 mm, was 14 s. The viscosity values are presented in Table 1.

Table 1.
Values of the conventional and kinematic viscosity of the liquid ceramic slurries

	slurry 1	slurry 2
conventional viscosity [s]	14	35
kinematic viscosity [mm^2/s]	9	15

Rheological investigations of slurries were carried out for three values of a temperature: 25, 30 and 35°C. The ceramic slurry consists of the water binder of the commercial name Ludox AM and a highly refractory aluminium oxide (Tab. 2).

Table 2.
Slurries composition and aluminium oxide grain size

	slurry 1	slurry 2
slurry composition	60 g of a binder and 800 g of Al_2O_3	60 g of a binder and 1300 g of Al_2O_3.
aluminium oxide grain size	d_L- 4,59-49 µm d_L- grain size	

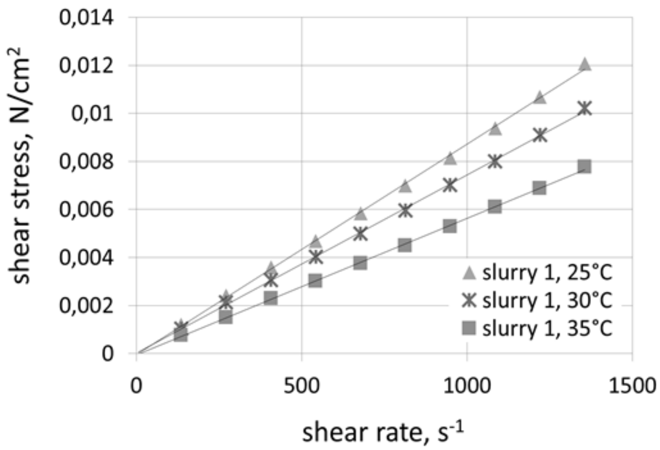

Fig. 3. Influence of the shear rate on shearing stresses of the liquid ceramic slurry 1, made on the basis of the water binder Ludox AM at temperatures of 25, 30 and 35°C

Regardless of a temperature, at which investigations were performed, along with increases of shear rates shearing stresses were also increasing. In addition, the flow curves were passing by the beginning of the coordinate system. On the basis of these two features the ceramic slurry 1 can be categorised to the group of Newtonian fluids. The slurry temperature (of a measurement) influences shearing stresses values. The higher temperature the lower shearing stress value in the slurry.

Figure 4 presents the dependence of shearing stresses on shear rates for the ceramic slurry 2. In a similar fashion as in case of the slurry 1, tests were performed for three temperatures. The linear increase of shearing stresses with the shear rate increase was observed. The essential difference between these slurries is the fact that the flow curves do not pass by the beginning of the coordinate system.

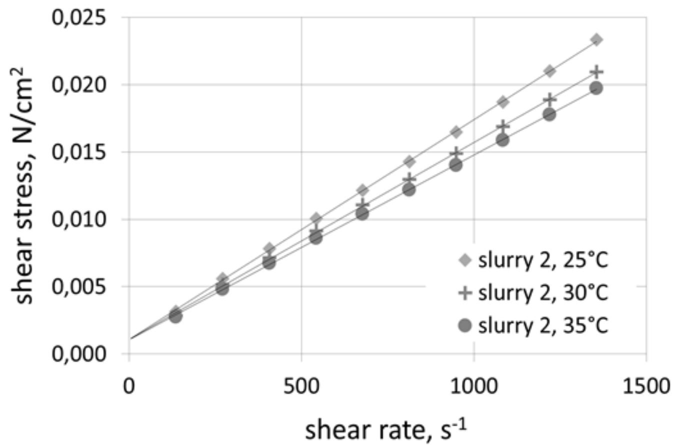

Fig. 4. Influence of the shear rate on shearing stresses of the liquid ceramic slurry 2, made on the basis of the water binder Ludox AM at a temperature: 25, 30 and 35°C

Due to this, the ceramic slurry 2 cannot be categorised into the Newtonian fluids but to rheostable fluids with a flow limit, it means into plastic-viscous fluids. Analogically, as in the case of the slurry 1, the temperature influences the shearing stresses occurring during tests in the slurry 2. Along with a temperature increase the shearing stresses are decreasing.

Figures 5 – 7 present comparisons of the shear rate influence on shearing stresses generated in ceramic slurries 1 and 2. Regardless of the ceramic slurry temperature (25°C – Fig. 5, 30°C – Fig. 6, 35°C – Fig. 7) the shearing stresses values at arbitrary shear rates, are in the case of sand 2 at least two times higher than in the ceramic slurry 1.

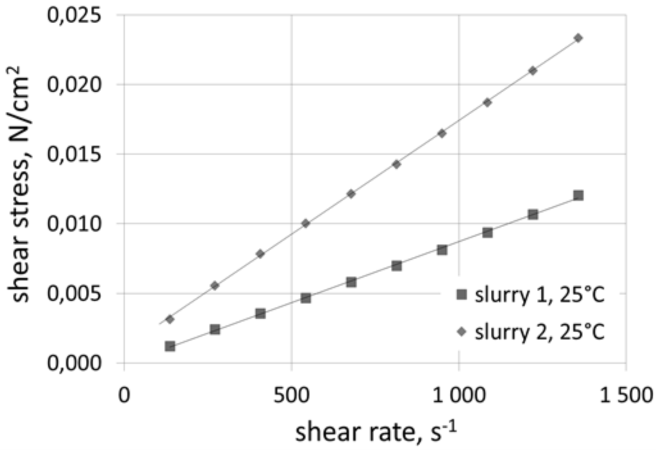

Fig. 5. Influence of the shear rate on the shearing stresses of the liquid ceramic slurries 1 and 2 at a temperature of 25°C

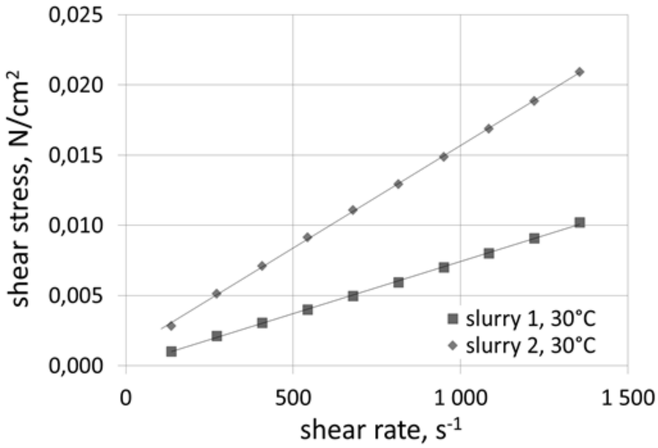

Fig. 6. Influence of the shear rate on the shearing stresses of the liquid ceramic slurries 1 and 2 at a temperature of 30°C

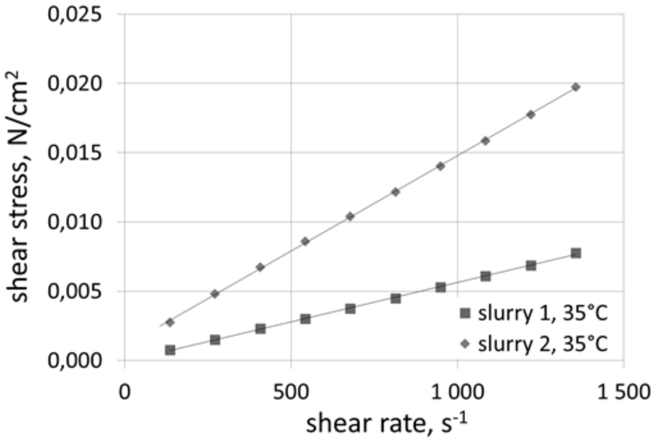

Fig. 7. Influence of the shear rate on the shearing stresses of the liquid ceramic slurries 1 and 2 at a temperature of 35°C

In turn, the influence of the shear rates on the dynamic viscosity of liquid ceramic slurries is presented in Figures 8 and 9 (Fig. 8 – slurry 1, Fig. 9 – slurry 2). The dynamic viscosity of the ceramic slurry 1 is not changing when the shear rate increases, which confirms that this slurry is the Newtonian fluid. What is more, a temperature increase of this slurry causes a viscosity decrease. The ceramic slurry 2 has different properties. When the shear rate increases this sand viscosity decreases, regardless of its temperature. This type of dependence confirms that the slurry 2 is not the Newtonian fluid. Nevertheless, in a similar fashion as in case of the slurry 1, the dynamic viscosity decrease is observed when a temperature increases.

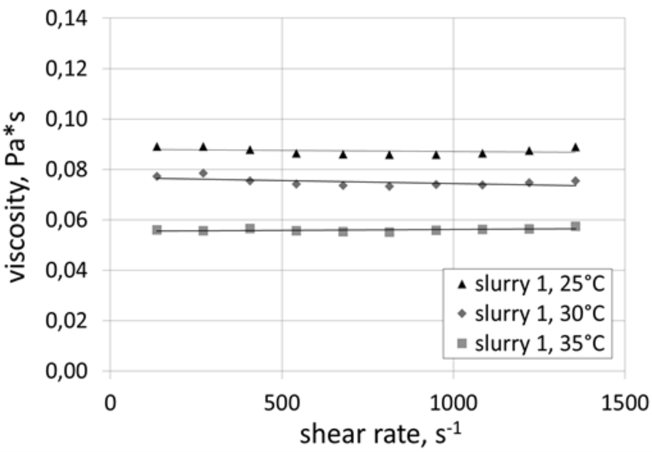

Fig. 8. Influence of the shear rate on the dynamic viscosity of the liquid ceramic slurry 1, prepared on the basis of the water binder Ludox AM, at temperatures: 25, 30 and 35°C

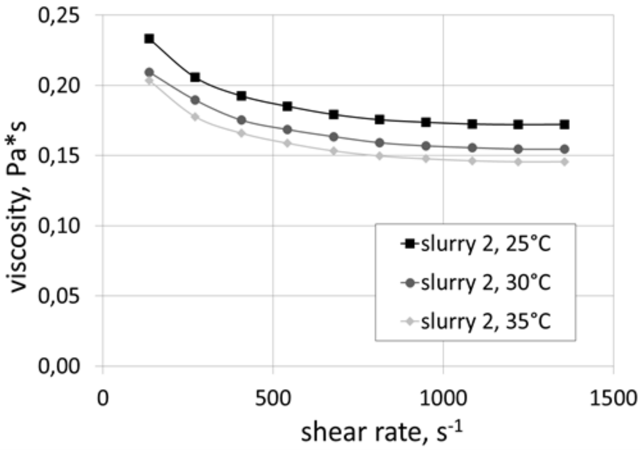

Fig. 9. Influence of the shear rate on the dynamic viscosity of the liquid ceramic slurry 2, prepared on the basis of the water binder Ludox AM, at temperatures: 25, 30 and 35^{o}C

5. Summary

Ceramic slurries constitute suspensions of solid particles, the most often: aluminium oxide, mullite or other ceramic material (molochit, quartz powder) of a very fine fraction (of the order of 5 – 49 µm) in a binder, which is a water solution of colloidal silica. The matrix content – solid particles in a binder equals 65 – 70%. With an increase of the matrix percent participation the conventional viscosity of ceramic slurries increases. The conventional viscosity of the ceramic slurry 1, measured by the Ford's cup with the opening outlet being 4 mm, equals 14 s, while for the ceramic slurry 2 it is more than two times larger (35 s). On the basis of the performed investigations, it can be inferred that the ceramic slurry of a low conventional viscosity, it means of a smaller content of solid particles in the binder, can be categorised into the Newtoniam fluids while the slurry of a relatively high conventional viscosity, it means of a larger content of solid particles in the binder - into non-Newtonian fluids. A more detailed classification of the sand 2 into rheostable fluids with the flow limit, it means plastic-viscous fluids, can be performed on the basis of the flow curve analysis. As the result of these considerations a speculation arises, that rheological properties of the ceramic slurry will be dependent on the solid particles contained in the binder, which - in turn - is essential in the process of making multilayered ceramic moulds.

6. Conclusions

On the basis of the performed investigations and the literature data several conclusions can be formulated.

- The analysis of the dynamic viscosity curve, i.e. the influence of shear rate on the dynamic viscosity of ceramic slurries and the flow curves allows to classify ceramic slurries in respect of their rheological properties.
- In case of the ceramic slurry 1 of the conventional viscosity 14 s, the dynamic viscosity is not changing when the shear rate increases. In addition the flow curve is passing through the beginning of the coordinate system, which allows to qualify this slurry into the Newtonian fluids.
- In case of the ceramic slurry 2 of the conventional viscosity 35 s, the viscosity decreases when the shear rate increases, which qualifies this sand into non-Newtonian fluids. In addition the flow curve changes linearly and is not passing through the beginning of the coordinate system. This allows for a more detailed classification of this sand into rheostable fluids with the flow limit, it means to plastic-viscous fluids.
- The binder based on colloidal silica has a long service life and does not gelate, however can change its viscosity. Along with a viscosity increase the deposited layers are becoming more and more thick. This renders difficult their drying and can cause mould cracks during drying. The dynamic viscosity of ceramic slurries is one of their most important features, which decides on the moulds quality, and therefore requires the continuous control.

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