CONTROLLING THE MICROSTRUCTURE OF PORCELAIN IN THE COURSE OF PLASTIC PASTE FORMATION

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A comparison of microscopically evaluated orientation of particles with calculated forming rate profiles provided evidence for the effect of the forming rate field on the orientation of particles during mix flow through the orifice of the forming machine. The region of disarranged orientation of particles is narrowed down with increasing forming rate, and its radius is in good agreement with the radius corresponding to the end of piston flow. The calculated mathematical model of the mix flow allows the forming conditions to be controlled, and thus various degrees of particle orientation to be achieved. The model approach is convenient for preparing materials according to their respective way of use and stressing, because various combinations of particle orientation determine the directional strength of ceramics.

INTRODUCTION

Mechanical strength represents the basic criterion for the quality of technical porcelain. Higher strength is achieved in particular by modifying the composition of the porcelain mix, by introducing new forming technologies and by optimizing the drying and firing processes.

Whereas the problem of modifying the mix composition has been dealt with by a number of authors [1, 2, 3, 4], the effect of technology on the final properties of porcelain has been paid considerably less attention. In the course of forming a plastic porcelain mix containing an addition of anisometric α-Al_2O_3 particles in a vacuum auger, the particles become oriented in a cetain part of the body cross section. This part can be characterized by a non-zero formation rate gradient, which is proportional to the rate of flow through the orifice of the forming device. Calculation of the forming rate conditions is possible with the use of a mathematical model of the given process.

The present study had the aim to indicate the possibilities of controlling the microstructure in porcelain green body containing α-Al_2O_3 during its vacuum auger formation in relation to the resulting mechanical properties of the final material. The method of mathematical modelling the mix flow through the auger orifice was used to express the effect of forming parameters on the arising body microstructure.

THEORETICAL

Description of the forming of cylindrical bodies is associated with mathematical treatment of the flow of plastic material through the orifice of the forming machine. The process can be simulated as horizontal flow of an isotropic incompressible liquid in direction x through a tube having radius R and length L.

On regarding the forming as a continuous process and if, after start-up, a significant part of the forming takes place under conditions of steady-state flow under isothermal conditions, i.e. the heat generated by friction is dissipated into the environment and temperature gradients are negligible, the process can be described on the basis of the generalized Navier-Stokes equation [5] and the constitutive equation of a general viscoplastic fluid in the form

$$\tau_s = \tau_0 + K\,(\mathrm{d}v_x/\mathrm{d}r)^n\,, \tag{1}$$

where τ_s is the shear stress at the tube wall, τ_0 is the yield stress, K is the coefficient of consistency, n is the flow index, and $\mathrm{d}v_x/\mathrm{d}r$ is the gradient of the deformation rate.

On the assumption that the flow does not involve shear along the tube wall (i.e. $v_s = 0$, where v_s is the rate of low at the tube wall), and the symmetry conditions are met, the flow rate profile of a porcelain mix passing through a circular orifice of the auger machine can be described by the following equation [5]:

over the interval $r_0 \le r \le R,\ \tau_0 \le \tau_{rx} \le \tau_s$

$$v_x(r) = 2L\left[K^{1/n}(1+1/n)\,\Delta p\right] \times \tag{2}$$

$$\times \left[(\tau_s-\tau_0)^{1+1/n} - ((r\Delta p/2L)-\tau_0)^{1+1/n}\right]$$

and over the interval $0 \le r \le r_0,\ 0 \le \tau_{rx} \le \tau_0$,

$$v_x(r_0) = 2L\left[K^{1/n}(1+1/n)\,\Delta p\right]^{-1} \times \tag{3}$$

$$\times \left[(\tau_s-\tau_0)^{1+1/n}\right]$$

where r_0 is the radius corresponding to the end of the piston flow. It holds that

$$r_0 = (\tau_0/\tau_s)\,R\,. \tag{4}$$

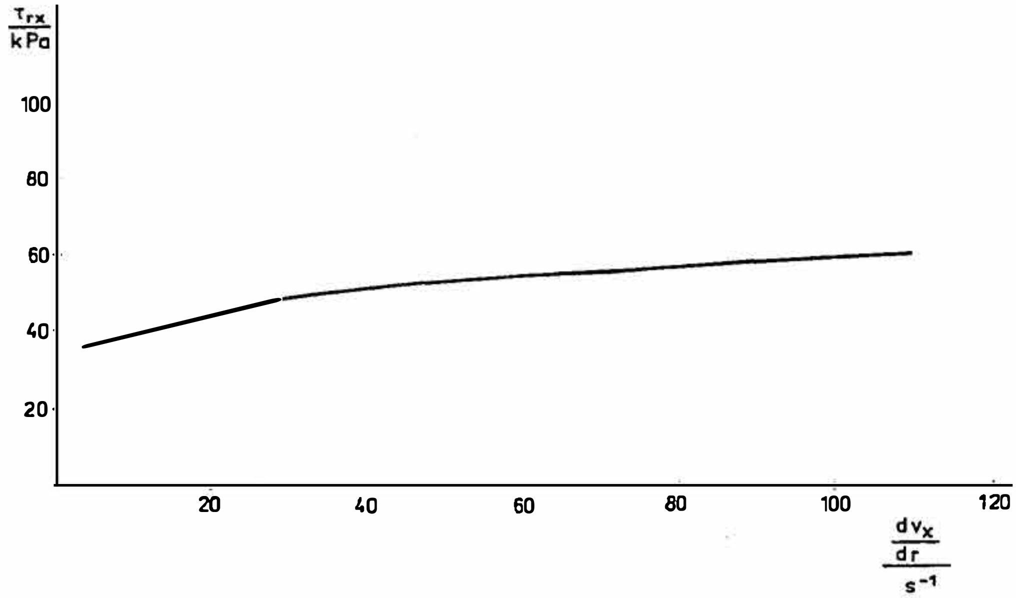

Fig. 1. Diagram of the constitutive equation of the porcelain mix.

For the mean flow rate $\bar{v}_x$ it holds that

$$\bar{v}_x = 2L\left(R\Delta p(1+1/n)K^{1/n}\right)^{-1} \times \tag{5}$$

$$\times\left[R(\tau_s-\tau_0)^{1+1/n} -\right.$$

$$\left.-2L\left(\Delta p(2+1/n)\right)^{-1}\times(\tau_s-\tau_0)^{2+1/n}\right]$$

where Δp is the pressure gradient, L is the length of tube having radius R.

DETERMINATION OF THE CONSTITUTIVE EQUATION FOR THE MIX

The porcelain mix employed contains 30 wt.% of α-Al_2O_3 with particles 30 to 40 μm in size, mostly of platelet form and 26% moisture (related to dry weight).

The constitutive equation of the mix was determined by the capillary viscometer method, based on measuring the dependence of the acting force on the mean rate of flow of the mix through a capillary [6, 7].

Evaluation of the relationship $\tau_{rx} = \mathrm{f}(\mathrm{d}v_x/\mathrm{d}r)$ in Fig. 1 corresponds to the constitutive equation of a general viscoelastic fluid (1) with the following values of the constants:

$T_0 = 16.00$ kPa, $K = 14.57$ kPa s^n, $n = 0.235$.

EXPERIMENTAL VERIFICATION OF THE RESULTS OBTAINED FROM THE MODEL

If the particles in a flowing mix become oriented, the directional arrangement, in particular of plate-shaped particles, is determined by the flow-rate field. For the mix flow through a circular orifice with radius $R = 5.5\times10^{-3}$ m and length $L = 6\times10^{-2}$ m, the flow-rate profile was calculated from equations (2) and (3) over the interval of medium flow rates $\bar{v} \in \langle 1.45\times10^{-4}$ m s^{-1} ; 4.73×10^{-2} m s$^{-1}\rangle$.

Typical flow rate profiles, e.g. those for the mean mix flow rate $\bar{v}_1 = 5.74\times10^{-3}$ m s^{-1} and $\bar{v}_2 = 4.73\times10^{-2}$ m s^{-1} are plotted in Figs 2 and 3.

The calculated flow-rate profiles indicate that piston flow with a zero rate gradient occurs for the individual mean flow rates over the radius interval given in Table I.

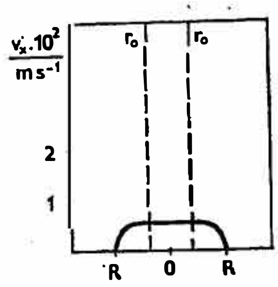

Fig. 2. Flow-rate profile for $\bar{v} = 5.74\times10^{-3}$ m s^{-1}.

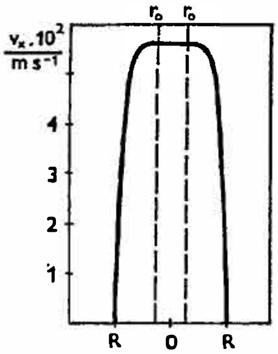

Fig. 3. Flow-rate profile for $\bar{v} = 4.73 \times 10^{-3}$ m s^{-1}.

Within these radius r intervals, the mix is carried in the flow as a whole and its initial disarranged orientation of particles must therefore be maintained. In contrast to this, over the interval $r \in \langle r_0;\ R\rangle$, orientation of particles is brought about by the flow-rate gradient.

The parameters evaluated from the model were verified experimentally by forming ceramic bodies from a prepared mix at given mean flow rate $\bar{v}$. The bodies were then dried at $T = 50°C$, 55% relative humidity

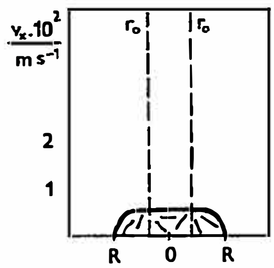

Fig. 4. Arrangement of particles for $\bar{v} = 5.74 \times 10^{-3}$ m s^{-1}.

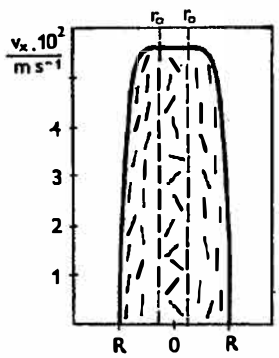

Fig. 5. Arrangement of particles for $\bar{v} = 4.73 \times 10^{-2}$ m s^{-1}.

Table I

Intervals of piston flow radii

$\bar{v} \times 10^3$ [m^2s^{-1}]	Calculated $r \in \langle 0; r_0 \times 10^{-3}\rangle$ [m]	Experimentally established $r \in \langle 0; r_0 \times 10^{-3}\rangle$ [m]
0.1446	0 ; 3.26	0 ; 3.40
2.3600	0 ; 2.41	0 ; 2.50
4.7500	0 ; 2.50	0 ; 2.50
5.7400	0 ; 2.18	0 ; 2.20
11.8000	0 ; 1.96	0 ; 1.80
47.0000	0 ; 1.57	0 ; 1.60

Table II

Bending strength of green and fired bodies

$\bar{v} \times 10^3$ [m s^{-1}]	σ_s [MPa]	σ_p [MPa]
0.145	4.6	120.7
2.360	5.4	125.8
4.750	6.1	127.7
5.740	6.2	129.8
11.800	6.8	135.1

and an air flow rate of 1.2 ms^{-1}. The bodies were fired in oxidizing atmosphere at 1230°C for 0.5 hour. The fired bodies were cut axially lengthwise, and the orientation of particles was evaluated microscopically (Figs. 4 and 5). The radius r_0 corresponds to the transition of random oriented to arranged platelets.

The microscopically evaluated intervals of radii with piston flow are listed in Table I.

MECHANICAL PROPERTIES OF THE BODIES

The bending strength of bodies formed at various rates was determined in green state (σ_s) as well as in the fired one (σ_p). The results are given in Table II.

CONCLUSION

A comparison of microscopically established orientation of particles with calculated flow-rate profiles proved an effect of the flow-rate field on the orientation of plate-formed particles during mix flow. The region of disarranged orientation of particles (r_0 in radius) is narrowed down with increasing medium forming flow rate, generally in good agreement with radius r_0 corresponding to the end of piston flow. In other words, with increasing rate of forming the thickness of surface layer containing oriented particles increases towards the body axis. This phenomenon is associated with a distinct increase in green bending strength, and a partial increase in the fired bending strength.

The findings show that mechanical strength of technical porcelain is not solely a question of the raw material composition of the mix, but can be also affected by the technology employed in the forming of plastic mixes.

The mathematical model of the mix flow allows the forming conditions to be controlled and a certain orientation of particles to be achieved. In this way it is possible to ensure unidirectional orientation of particles throughout the body or only in the surface layers of the body.

The model procedure therefore allows materials to be modified according to their prospective use and stressing, because various combinations of orientation determine the directional strength of ceramics.

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ŘÍZENÍ MIKROSTRUKTURY PORCELÁNU PŘI TVAROVÁNÍ PLASTICKÝCH SMĚSÍ

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Cílem práce bylo stanovení matematického modelu toku plastické keramické směsi ústím vakuového šnekového lisu k předpovědi orientace destičkovitých částic.

V tělesech vytvarovaných při různých rychlostech byla mikroskopicky vyhodnocena orientace řástic a stanovena pevnost v ohybu po sušení a po výpalu.

Z porovnání experimentálně určeného uspořádání částic s odpovídajícími vypočtenými oblastmi uspořádané a neuspořádané orientace částic vyplynulo potvrzení vlivu rychlostního pole na orientaci částic.

S rostoucí střední rychlostí tvarování se zužuje oblast neuspořádané orientace částic, jejíž poloměr je v dobré shodě s poloměrem odpovídajícím konci pístového toku.

Dále byl potvrzen vliv rychlostního pole na směrovou mechanickou pevnost keramiky.

Vypočtený matematický model toku směsi ústím vytvářecího zařízení umožňuje řízení podmínek tvarování a dosažení různé orientace částic.

Modelový přístup umožňuje připravovat materiály podle způsobu užití a namáhání, neboť různá kombinace orientace částic určuje směrovou mechanickou pevnost keramiky.

Obr. 1. Graf konstitutivní rovnice porcelánové směsi.
Obr. 2. Rychlostní profil pro $\bar{v} = 5,74 \times 10^{-3}$ $m.s^{-1}$.
Obr. 3. Rychlostní profil pro $\bar{v} = 4,73 \times 10^{-2}$ $m.s^{-1}$.
Obr. 4. Uspořádání částic pro $\bar{v} = 5,74 \times 10^{-2}$ $m.s^{-1}$.
Obr. 5. Uspořádání částic pro $\bar{v} = 4,73 \times 10^{-2}$ $m.s^{-1}$.