MATERIAL DESTRUCTION BY MICROWAVE ASSISTED DRYING

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Abstract: The aim of this paper is to analyze the destruction of ceramic-like materials during microwave drying. The distributions of temperature and moisture content in the samples are visualized with infrared camera and presented graphically. The experiments are carried out on kaolin-clay samples, which destruction is visualized on photographs taken with the photo camera and microscope. The thermo-hydro-mechanical model of drying is used to determine the effective stress required to predict the material failure and the spots prone to damage. The numerically predicted spots are compared with the experimentally appointed places of material damage and a good adherence of the numerical predictions with experiments is confirmed.

Keywords: microwave drying, kinetics, stresses, damage, experiment, modeling,

INTRODUCTION

In order to improve the efficiency of convective drying the microwave radiation is often used for enhancement of this process (Perre and Turner, 1997; Garcia and Bueno, 1998; Feng et al., 2001; Sanga et al., 2002). The advantages of microwave drying manifest themselves in smaller energy consumption, better quality of dried products, and much shorter drying time than in purely convective drying. All these positive effects may be gained provided that the applied microwave power is at an admissible level. Otherwise the material may experience strong damage that could make the dried product useless.

The main aim of this paper is to study the problem of damage of clay-like materials dried at different microwave power (MwP) levels. The distributions of temperature and moisture content in cylindrically shaped clay-like samples are determined experimentally and numerically and visualized with the use of infrared camera and on numerically drawn up graphs.

The spots of an enhanced risk to crack formation are determined numerically on the basis of thermo-hydro-mechanical drying model elaborated earlier by authors. The effective stress is formulated using the energetic failure criterion of Huber-von Mises-Hencky to predict the spots of likely material damage. The patterns of fractures arisen in the samples after microwave drying at four different microwave powers are presented. A good adherence of the material spots prone to damage predicted numerically with the places of real material damage determined experimentally is shown.

EXPERIMENTAL

KOC kaolin-clay from the Surmin-Kaolin SA Company, Nowogrodziec, Poland was the material investigated experimentally and theoretically in this paper.

The cylindrical kaolin-clay samples of diameter 0.06 m and height \( h = 0.06 \) m and initial moisture content (MC) approximately equal to 0.45 [kg/kg]\(_{db}\) were dried in the laboratory microwave dryer Plazmatronika WS 110 for the following magnetron output power levels: 120W, 180W, 240W and 300W. The view of samples after drying with different microwave powers is presented in figure 1.

Fig. 1. Kaolin samples dried with different microwave power levels.

As it is seen in figure 1 only the sample dried with 120 W has acceptable quality. From the four samples dried with 180 W two of them got a number of debris split off from the main body, and the two others did not fractured at all becoming only a slight barrel shape. The samples dried with 240W look fractured totally. In the sample dried with 300 W there is one
huge vertical slit and some split parts at the upper surface.

Figure 2 presents the internal views of samples dried with 240 W after 10 and 50 minutes of drying.

It is visible that after 10 minutes of drying some fractures in central parts of the sample have appeared (Fig. 2a). After 60 min of drying there were more visible fractures and also the internal structure of the sample became very incoherent (Fig. 2b). This rough structure was procured by rapid evaporation of water inside the sample that induced a high pressure. The temperature inside the material was very high (nearly 80°C). The distributions of temperature were typical for microwave drying: higher temperature inside and the lower one close the surface.

MODELING

The distribution of drying-induced stresses and the effective stress responsible for material failure were calculated for a kaolin-clay cylinder subjected to microwave drying (Fig. 3)

The thermo-hydro-mechanical model (Kowalski, 2007) was used for determination of the state of stress in the cylindrical samples during microwave drying. The description of cylinder deformation, expressed by the radial and longitudinal displacements $u_r$ and $u_z$, is provided by the two coupled equations of the form (Kowalski and Rybicki, 2009)

\[ MV^2 u_r + \frac{\partial}{\partial r} \left[ (M + A) \varepsilon - \gamma_T \partial - \gamma_X \theta \right] = M \frac{U_r}{r^2} \]

\[ MV^2 u_z + \frac{\partial}{\partial z} \left[ (M + A) \varepsilon - \gamma_T \partial - \gamma_X \theta \right] = 0 \]

where $M$ and $A$ denote the shear and bulk elastic modules, $\gamma^{(T)} = (2M + 3A)\kappa^{(T)}$, $\gamma^{(X)} = (2M + 3A)\kappa^{(X)}$ are the thermo and hydro modules with $\kappa^{(T)}$ and $\kappa^{(X)}$ representing the coefficients of linear thermal- and hydro-expansion, $\theta$ and $\theta$ denote the departure of liquid content and temperature from the reference state. In these equations $\nabla^2$ denotes the Laplace’s operator for cylindrical geometry and $c$ is the volumetric strain.

The mechanical boundary conditions express zero valued radial $\sigma_{rr}$ and longitudinal $\sigma_{zz}$ stresses on the external surfaces, and zero valued radial $u_r$ and longitudinal displacements $u_z$ on the cylinder axis and at the bottom surface of the cylinder, that is,

\[ \sigma_{rr} \bigg|_{r=R} = 0, \quad \sigma_{zz} \bigg|_{z=H} = 0, \quad u_r \bigg|_{r=0} = 0, \quad u_z \bigg|_{z=0} = 0 \]

Having determined the displacements and strains one can calculate stresses using the suitable physical relations (Kowalski, 2003). The state of stress in the cylinder is fully described by four components of the stress tensor, namely: radial $\sigma_r$, circumferential $\sigma_{\phi \phi}$, longitudinal $\sigma_{zz}$, and shear $\sigma_{\phi z}$ stresses.

The effective stress is defined from the Huber-von Mises-Hencky energy hypothesis (Augier et al., 2002; Banaszak and Kowalski, 2005)

\[ \sigma_{\text{eff}} = \frac{1}{2} \left( \sigma_{rr} - \sigma_{zz} \right)^2 + \left( \sigma_{rr} - \sigma_{\phi \phi} \right)^2 + \left( \sigma_{\phi \phi} - \sigma_{zz} \right)^2 + 6 \sigma_{\phi z}^2 \]

The material failure can take place if the effective stress exceeds the admissible one, which expresses the yield stress or the strength of the material at a given moisture content. The admissible stress was determined experimentally by Musielak (2001) for kaolin-clay at different moisture contents. The experimental data for admissible stress have been interpolated by the following function

\[ \sigma_{\text{adm}} = \sigma_0 + \sigma_X \exp(-C_\sigma \theta) \]

where $\sigma_0 = 142$ 858 Pa, $\sigma_X = 1$ 688 320 Pa and $C_\sigma = 29$.6534.

The failure of the material may happen if it becomes plastic or if the material strength will be violated in those regions of dried kaolin-clay cylinder in which

\[ \sigma_{\text{eff}} \geq \sigma_{\text{adm}} \]

The distribution and time evolution of the moisture content in the kaolin-clay cylinder during drying was presented in Kowalski et al. (2010).
RESULTS AND DISCUSSION

The numerical calculations of moisture and temperature evolution and distributions and the state of stress in the cylindrical kaolin-clay samples were carried out. Figure 4 presents the drying kinetics curves determined numerically and experimentally for microwave drying at 120W.

![Drying kinetics determined numerically and experimentally.](image)

We see that the drying model used in this paper reflects very well both the drying curves and the material temperature curves, which were determined experimentally.

The stress components allow to calculate the overall effective stress, which maintains the failure of dried material. Figure 5 illustrates the regions in the cylinder half where the effective stresses are greater than the admissible ones, that is, the regions where $(\sigma_{\text{adm}} - \sigma_{\text{eff}}) < 0$ for the two different microwave power levels: 180W and 240W.

![Regions in the cylinder cross section where $(\sigma_{\text{adm}} - \sigma_{\text{eff}}) < 0$ at 60 min drying time for the two different microwave powers: a) 180W, b) 240W.](image)

These regions are around point $(R, 0)$ and in the process with 240W also at the top of the sample $(R, H)$. This figure shows the low relief map of possible material failure in the cylinder at 60 min drying time. This prediction was confirmed experimentally by microwave drying of the kaolin cylinder in severe drying conditions by application of 240 W, and in particular 300 W microwave power (Fig. 1).

CONCLUSIONS

Microwave power influences significantly the quality of dried kaolin samples. All samples dried with microwave power above 120 W experienced damage. Two of the four samples dried with 180 W exhibited many fractures and split off pieces, but two others had no visible fractures at the external surfaces.

Many samples sustained bulgy deformation, which was associated with the intensive water evaporation and growth vapor pressure inside the material. Intensive evaporation caused a rapid increase of pore pressure, which resulted with disheveled and incoherent structure of the material inside. Sudden increase of vapor pressure inside these samples caused strong damage of explosive character, as it happened during drying with 300 W (Fig. 1).

The thermo-hydro-mechanistic model of drying served a calculation of the drying stresses. Through comparison of the effective stress with the admissible stress the numerical analysis enabled indication of the places, where the material damage can likely occur, as it is shown in figure 5.

ACKNOWLEDGEMENTS

This work was carried out as a part of research project No N N209 104337 sponsored by Polish Ministry of Education and Science.

REFERENCES


