IMPROVEMENT OF FIRING CURVE OF CERAMIC WARE VIA MODELLING AND NUMERICAL SIMULATION OF THE COUPLED THERMO-MECHANICAL PROCESSES IN THE MATERIAL

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ABSTRACT

A mathematical model of coupled heat transfer and mechanical processes in ceramic ware at firing is developed. It is based on information about the thermo-mechanical behaviour of the material at sintering, obtained experimentally. The model is solved numerically for massive bodies of technical ceramics to estimate and prevent the reasons for cracks appearance at their firing in chamber kilns. The transient thermo-mechanical processes in the fired mass are simulated varying with the heating rate of the firing curves. The investigated thermal regimes are analysed on the base of the results about the temperature and stresses fields in the articles. Approaches for improvements of the fired curve are discussed in order to prevent defects of the products.

Keywords: ceramic, firing, heat transfer shrinkage, thermal stresses, modelling, finite element method.

INTRODUCTION

The firing is the most energy intensive process in the ceramic manufacturing [1]. It is consisted of heating of the ceramic articles to so-called firing temperature, keeping it in order to reach a uniform temperature field in the fired domain and cooling of the articles. These processes are realised at automatically maintained firing curves, represented by changes of the temperature in the kiln space with the time. The thermal regime is organized to provide faultless firing of articles at possible decreasing of the energy consumption. Chemical reactions, phase and structure changes proceed in the fired domain at the conditions of transient non uniform temperature fields during the firing. That result in mechanical processes as temperature expansion, shrinkage and gravity driven plastic deformations. Knowing of these processes is important for a proper choice of the heating and cooling rates of the firing curve. Such data can be obtained for small amount of material by differential thermal analysis (DTA), differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) and dilatometrically analysis. However, the non-uniform temperature fields lead to non-uniform proceeding of the mentioned above multi-physical processes in the fired products with complex geometries, and to subsequent mechanical stresses that can cause their failures. The mathematical modelling and numerical simulation of the heat transfer are useful approaches at the investigations for efficient firing curves of ceramic ware in continuously and periodically working kilns [2]. Detail information about the transient three-dimensional temperature fields and their gradients in fired products can be obtained as result. An estimation of the probability for production failure is possible comparing the maximal computed temperature gradients in the bodies with their permissible values that are unknown for most of the cases and can be established experimentally [3].

The finite element analysis, based on mathematical modelling of the coupled heat transfer and mechanical processes in the ceramic mass is a successful ways to estimate the stress state in the articles during the drying and the firing, and the possibilities for production failure [4 - 9].

Fig. 1. A defective ceramic article.

This study is aimed to estimate and eliminate the reasons for cracks appearing in massive articles of technical ceramic during a high temperature firing via mathematical modelling and numerical simulation of thermo-mechanical processes in fired mass.

The causes for defects in solid bodies during their firing in high temperature gas chamber kiln are object of the present investigation (Fig. 1). The articles are formed by pressing of raw material, based on Al_2O_3. The firing curve is consisted of increasing of the temperature from 20°C to 1450°C for 14.5 h, keeping that temperature for 0.5 h and cooling for about 14 h. The initial length and maximal diameter of the raw body are 395 mm and 145 mm, respectively. Shrinkages of about 14.5 % for all sizes of the articles are established after the firing process. Detail technical information about the products and the kiln is not possible due to confidential rules.

DTA, TGA and dilatometrically analysis were done in the firing temperature interval (Fig. 2). A common shrinkage of the material of 14.3 % and the temperature intervals of its proceeding are obvious from the figure. The shrinkage starts at temperature of about 900°C and continues at relatively high rate until reaching 1341°C. The process also continues after that temperature, but at relatively slow rate. In the same time, there are not endothermic and exothermic reactions in the material during the shrinkage, obvious from the DTA curve. Therefore, the shrinkage is due to structural changes in the material, causing a compaction and subsequent change of its density.

A detailed examination of the cracks has revealed that they are mainly in the most massive parts of the products. The uneven temperature fields and shrinkage in these parts during the heating period are supposed to be the possible reasons for their appearance. The fast-

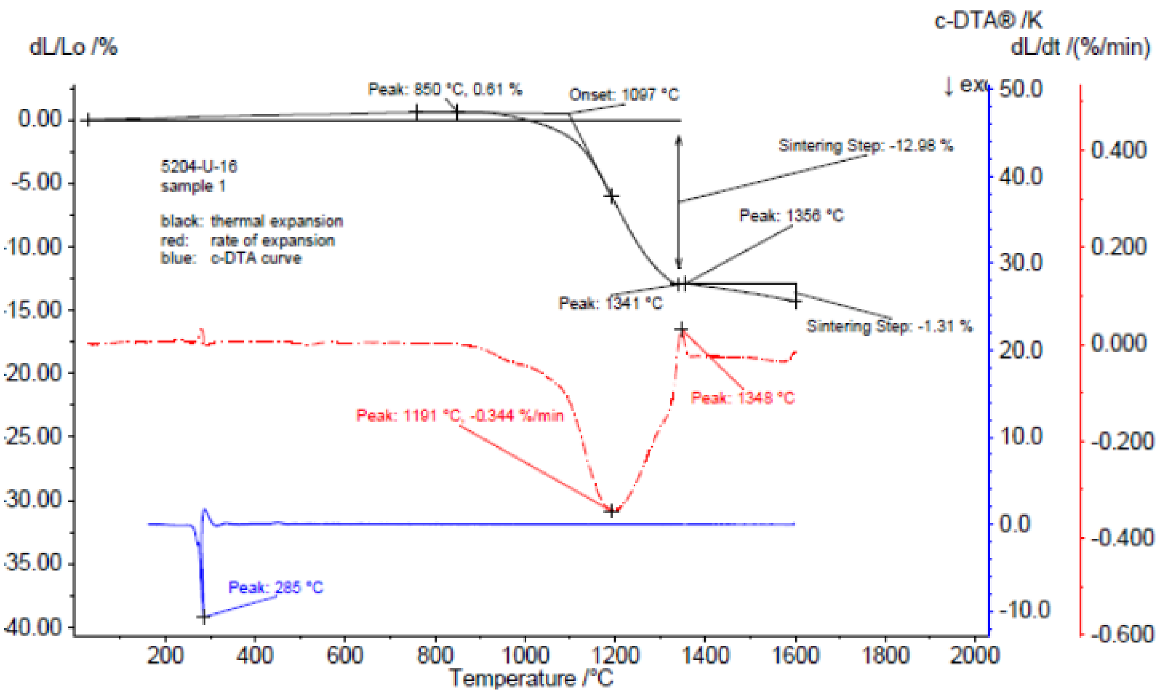

Fig. 2. Experimental investigation of the ceramic material.

heating surface layers of the article start to shrink upon reaching 900°C, while in the interior of the articles this process has not yet begun. As a result, surface stresses, exceeding the instantaneous strength of the material and subsequent cracks occur. Models of thermo-mechanical processes in the fired articles are composed, taking into account the features of the thermal regime and the experimentally obtained data in order to check and prove that hypothesis.

EXPERIMENTAL

Mathematical models and conceptions for numerical simulation

The transient heat transfer and subsequent mechanical processes in the ceramic during the heating period can be modelled at coupled solution of equations (1) and (2) for the three dimensional solid domain of the article [10].

$$\rho.c.\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) \quad (1)$$

$$\{\sigma\}=[D]\{\varepsilon\} \quad (2)$$

where T (K) is temperature, τ (s) is time, ρ ($kg\ m^{-3}$) is density, c ($Jkg^{-1}K^{-1}$) is specific heat capacity, K ($Wm^{-1}K^{-1}$) is thermal conductivity, {σ} is stress vector, [D] is elastic stiffness matrix, formed by module of elasticity E, Pa and Poisson ratio ν; {ε} is elastic strain vector.

In the coupled structural – thermal analysis, the total strain is formed of elastic $\{\varepsilon^{el}\}$ and thermal $\{\varepsilon^{th}\}$ parts, respectively:

$$\{\varepsilon\}=\{\varepsilon^{el}\}+\{\varepsilon^{th}\}=[D]^{-1}\{\sigma\}+\{\alpha\}\Delta T \quad (3)$$

where {α} (K^{-1}) is vector of the coefficient of thermal expansion, ΔT is temperature change according to a reference value T_{ref}.

$$\Delta T=T-T_{ref} \quad (4)$$

The material models are summarised in Table 1. The specific heat coefficient and the thermal conductivity of the material are accepted as function of the temperature according to [11].

The change of the density at the shrinkage is taken into account on the base of the initial and final masses and volumes of the articles. Linear increasing of the density with the temperature is accepted for the temperature interval of the shrinkage. The instantaneous coefficient of thermal expansion α is computed on the base the dilatometrically analysis of (Fig. 2), accepting that material shrinks with constant rates at a temperature intervals between 900°C and 1341°C (higher rate), and 1341°C - 1450°C (lower rate).

The thermal boundary conditions include surface temperature change with the time according the temperature curve on all surfaces according to equation (5), excepting the contact with the kiln floor (bottom surface on Fig. 3). The last is accepted as adiabatic.

$$T=\begin{cases} T_{in}+C\tau & at\ the\ heating\ period \\ T_{firing} & at\ the\ period\ of\ keepig\ the\ firing\ temperature \end{cases} \quad (5)$$

where T_{in} (K) is initial temperature of the articles, T_{firing} (K) is firing temperature, C (Ks^{-1}) is heating rate.

The boundary conditions for the structural analysis include zero normal displacements on the contact surface with the transport and zero displacements on all directions on the centre of this surface.

Table 1. Material models.

Physical properties	Dimensions
$c=756.4+0.262T$	$Jkg^{-1}K^{-1}$
$K=1.51+0.000215T$	$Wm^{-1}K^{-1}$
$\rho=\begin{cases}2100 & at\ 293K\le T\le 1173K\\ 2100+2.494(T-1173) & at\ 1173K\le T\le 1614K\\ 3200 & at\ 1614K\le T\le 1743K\end{cases}$	$kg\ m^{-3}$
$E=20\times10^9$ [12]	Pa
ν=0.9 [12]	-
$\alpha=\begin{cases}0 & at\ 293K\le T\le 1173K\\ -0.00032 & at\ 1173K\le T\le 1614K\\ -0.00026 & at\ 1614K\le T\le 1743K\end{cases}$	K^{-1}

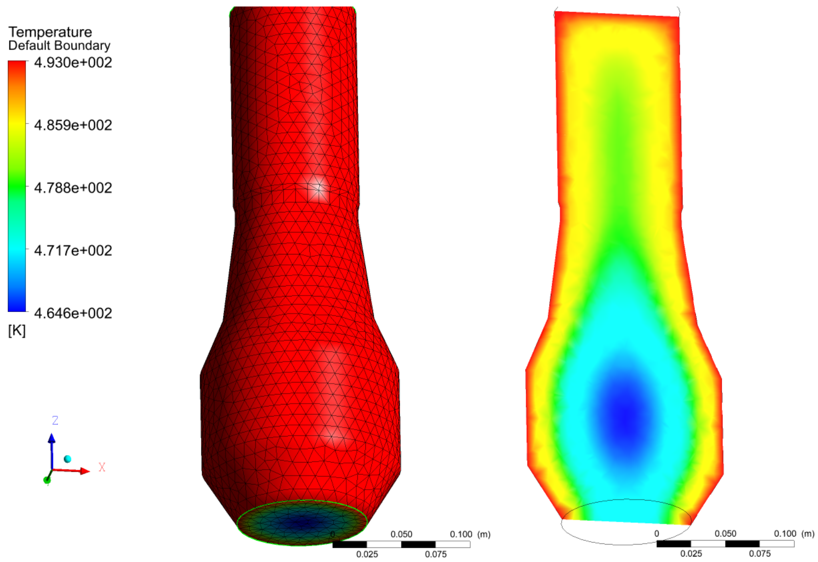

Fig. 3. Temperature field on the boundaries and a central cross section at τ = 7200 s.

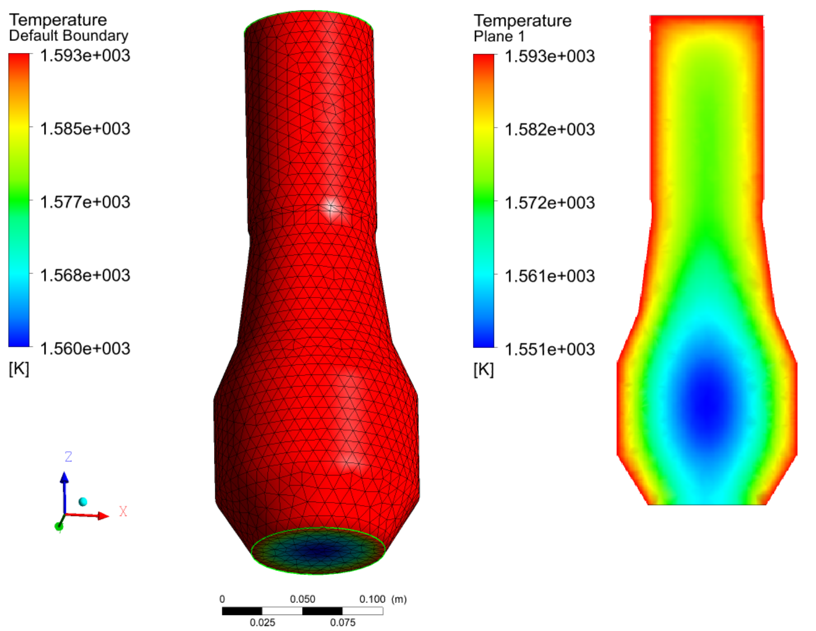

Fig. 4. Temperature field on the boundaries and a central cross section at τ = 46800 s.

A geometrical model is created and discretized by finite element type Solid 98. Such mesh ensures direct coupled numerical solution of equations (1) and (2) by finite element techniques [10].

RESULTS AND DISCUSSION

The nodal values of the temperatures, stresses and strains were obtained for the maintained firing regime as results of numerical solutions of the models. The temperature fields for chosen moments (2 h after the start of the process and the middle of the shrinkage period) are shown in Fig. 3 and Fig. 4. First principle stresses, accepted as the most indicative for the stress-strain behavior for the ceramics [12], are shown on Fig. 5 and Fig. 6 for the same moments. The negative stresses are compressive, the positive are tensile. The reduction of the sizes is obvious from these figures.

The models are validated comparing the final sizes, obtained at the modeling to the real ones. Differences below 2 % are established. So the results about the thermo-mechanical processes are with an enough agreement to the reality. The temperature differences and gradients

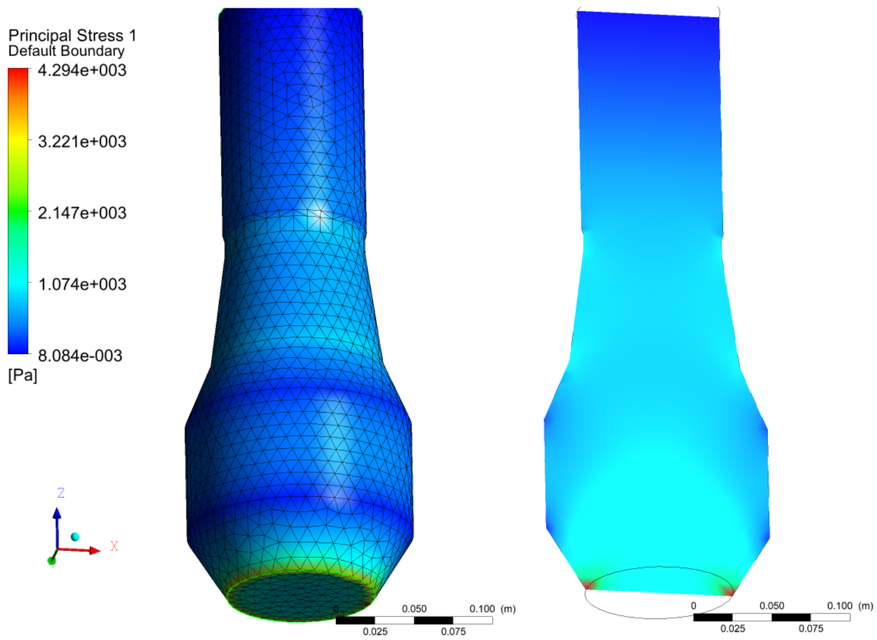

Fig. 5. First principal stress on the boundaries and central cross section at τ = 7200 s.

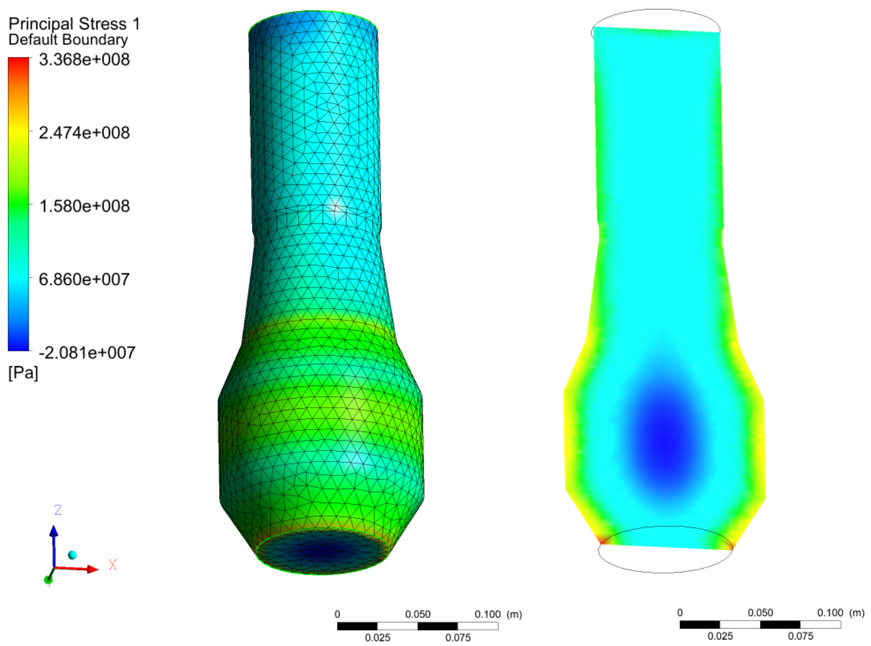

Fig. 6. First principal stress on the boundaries and central cross section at τ = 46800 s.

in the fired body are similar at these moments. But the stresses during the shrinkage are higher in comparison to the same at the lack of the shrinkage. The maximal absolute values of the stresses are established in the areas where crack appears. The comparison between them and the strength of the material can prove the possibility for failure of the products. However, there is not information about the strength of the material during the structural changes at the firing - only the strengths of the final material are given the literature. The flexural strength of the technical ceramic is 30 - 40 MPa, the compressive one is 300 MPa [12]. The maximal compressive and tensile stresses are near the respective strengths. Therefore, the non-uniform shrinkage due to higher temperature gradients in the massive parts of the body is the possible reason for these stresses and the cracks in these places.

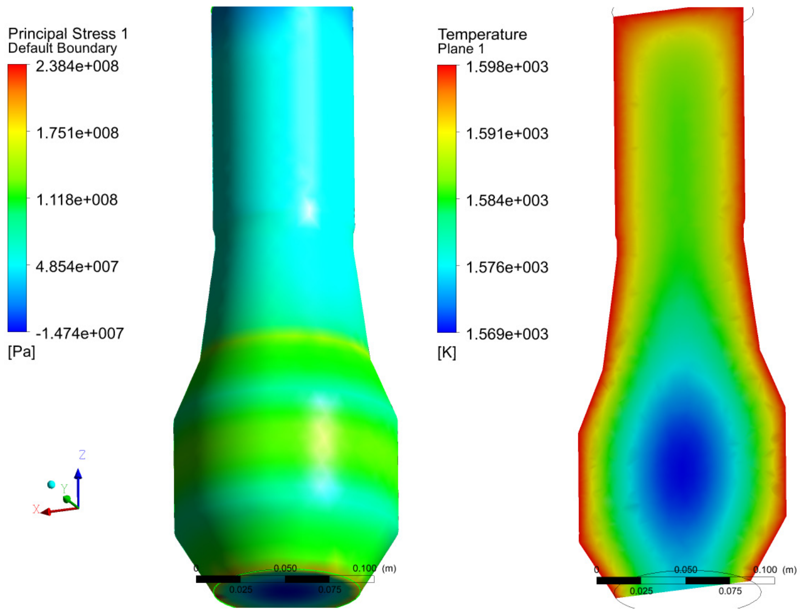

Fig. 7. First principal stress on the boundaries and temperature field in a central cross section at τ = 97200 s.

Additional numerical simulations of the processes are implemented at subsequently increasing of the heating period by reductions of the heating rate in order to decrease the temperature gradients in the articles. The heating time of the articles is gradually extended (20 h, 22 h, 24 h, 30 h), keeping the maximal temperature of 1450°C. A reduction of the temperature gradients and the maximal stresses during the shrinkage is established. The temperatures and the first principle stresses at the middle of the shrinkage period for the 30 h heating of the body are shown on Fig. 7. The maximal absolute values of the compressive and tensile stresses are about 30 % lower than the correspondent stresses at the present heating time (14.5 h). Byt the tensile stress is near the flexure strenght of the material. So even the twice extension of the heating time is not eliminating the problem. Moreover, the energy consumption of the kiln will increase also nearly twice. Therefore, the reduction of the heating rate is not a solution of the problem.

Possible variants for eliminating of the reasons for production failures are keeping the initial high heating rate until reaching the start temperature of the shrinkage and reduction of the heating rate more than twice at the temperature interval with the high shrinkage rate.

CONCLUSIONS

A mathematical model for numerical simulation of the thermo-mechanical processes in ceramic articles at firing in a presence of shrinkage is developed. It gives a detail information about the transient fields of temperatures, stresses and strains in the products and can be used for estimation and improvement of the firing curves.

The model was applied for investigations and eliminating of problems, occurring at firing of massive articles of technical ceramic by decreasing of the heating rate of the firing curves. Although the investigated regimes are not successful, the model is a base to continue the researches, varying the heating rate at the temperature intervals of the higher expected mechanical deformations of the products.

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