*Science, Engineering & Education, 7, (1), 2022, 3-12*

# Temperature-diffusion Analogy in Fracture Analysis of Ceramic Products during the Drying Process

Veselin Iliev*, Mihaela Zheleva

*University of Chemical Technology and Metallurgy, Sofia, Bulgaria*

*Received 03 July 2022, Accepted 20 October 2022*

**ABSTRACT**

*This article presents an approach, combining fracture mechanics and temperature-diffusion analogy, to assess the initialization of cracking and the crack propagation in the drying process in the production of ceramic products.*

*The correspondence between humidity and temperature in the resolving equations of the two processes is used as a basis for the temperature-diffusion analogy. These equations were solved using the "Transient Thermal" and "Static Structural" modules of the ANSYS Workbench software. The mechanical properties of the material necessary for the realization of the solution (coefficient of thermal conductivity and diffusion coefficient) are taken from literature sources. From the model temperature solution, results were obtained for the temperature distribution, which shows the picture of the moisture content in the real drying process. Results for deformations and mechanical stresses in the material have also been obtained. By introducing a crack and applying the apparatus of fracture mechanics, the values of the stress intensity factor at different crack orientations were obtained. The obtained results can be used to optimize the drying process and reduce product defects.*

Keywords: *fracture analysis, temperature-diffusion analogy, numerical simulation.*

## INTRODUCTION

The process of removing moisture from porous material is essential in the ceramics industry as a step in the process of brick production. A detailed description of this process is presented in [1, 2]. As stated there, the production of ceramic parts consists of the formation of hydrated clay, which is then subjected to slow drying in an oven or in an environment protected from sunlight to reduce the water content of the material. As the space previously occupied by the water becomes empty during this process, shrinkage occurs in the volume of the product. To reduce defects such as cracks and deformations, optimal conditions of the drying process must be provided, in which the lowest gradient of moisture and temperature inside the structure of the material is reached.

To optimize the process, it is necessary to know the characteristics of the material used in the manufacture of the product, as well as operating conditions (temperature, relative humidity and drying intensity).

The theory of diffusion of liquids is considered to be the simplest analysis, as it ignores other effects such as evaporation of moisture and transfer of vapors inside the material during the drying process. This model considers water migration as the main mechanism based on

**Correspondence to: Veselin Iliev, University of Chemical Technology and Metallurgy, 8 Kliment Ohridski blvd., 1756 Sofia, Bulgaria, E-mail: veso@uctm.edu.*

Fick's second law, according to which the mass per unit area is proportional to the gradient of water concentration [3]. Analytical solution methods are based on simple considerations that allow solutions of differential equations only for specific simplest cases in which the input variables are defined to calculate one or more output variables [4]. Complete results are obtained on the basis of numerical methods, in which the partial differential equations related to the physical problem are transformed into a system of equations based on mathematical theory, such as the finite element method or the finite volume method.

Analysis of diffusion in complex geometries cannot be solved by analytical techniques alone. In these cases, computational fluid dynamics (CFD) techniques are used. Several studies on the drying of ceramic bricks by CFD can be found in the literature, which allows better process control and optimized production, with reduced losses and lower costs, avoiding the waste of raw materials. When the mass flow is very slow, the phenomena of heat transfer and mass transfer are practically diffusion and analysis of fluid dynamics is not necessary, then only the laws of Fourier and Fick are involved.

With regard to mathematical modeling and numerical simulations involving ceramic bricks, we can mention articles that study the emissions of pollutants resulting from the combustion of organic materials, as well as the absorption of pollutants from ceramic materials [5]. In this sense, the main goal of these developments is to simulate the process of drying industrial hollow ceramic bricks in a kiln by applying the CFD technique (Ansys CFX software).

Advanced numerical simulation software allows structural-diffusion analysis in the internal volume of the brick, but the possibilities for defining the boundary conditions and properties of the material in solving mass transfer equations and stress-strain equations are very limited [6]. An alternative approach to such an analysis is to apply structural-diffusion simulation, using the analogies between mass and heat transfer and between diffusion and thermal stresses [7].

In general, the equations used in this approach and the quantities involved are shown in Table 1.

The analyzes made by this analogy give results for the field of stresses and strains in the whole considered area, from which no direct conclusion can be made for the occurrence and development of cracks at individual points. Such a conclusion can be made with the help of fracture mechanics.

This article presents an approach, combining fracture mechanics and temperature-diffusion analogy, to assess the initialization of cracking and the crack propagation in the drying process in the production of ceramic products.

The obtained results can be used to optimize the drying process and to reduce product defects.

## EXPERIMENTAL

The object of the present study is a double-size brick (Fig. 1), with dimensions of 0.25/0.25/0.12 m for the body and 0.25/0.044/0.033 m for the holes. To simplify the geometric model, the outer surfaces are assumed to be smooth, with ribbing reported in the mathematical model by correction of boundary conditions. The material used is clay, for which the main characteristics are: density (Table 2); specific heat capacity c = 600 J $kg^{-1}$ $K^{-1}$;

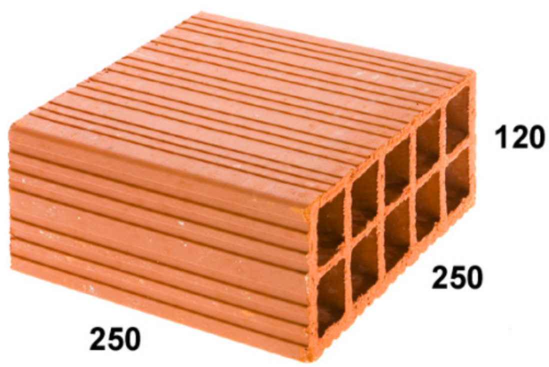


Fig. 1. Brick dimensions.

Table 1. Equations for real and analogous processes.

| | Real process to be analyzed (diffusion) | Analogous process by which the analysis is performed (heat transfer) |
|---|---|---|
| Basic value | $W$ [%] | $T$ [°C] |
| Mathematical model | $\frac{\partial W}{\partial T} = \lambda(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} + \frac{\partial^2 W}{\partial z^2})$ | $\frac{\partial T}{\partial t} = D(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2})$ |
| Material characteristics | $D_{\rho,c} = f(W)$ | $k_{\rho,c} = f(T)$ (Fig. 3) |
| | $E = f(W)$ | $E = f(T)$ (Fig. 4) |
| | $\nu = f(W)$ | $\nu = f(T)$ (Fig. 5) |
| | $MOR = f(W)$ | $MOR = f(T)$ (Fig. 6) |
| | $\alpha = f(W)$ | $\alpha = f(T)$ (Fig. 7) |
| Boundary conditions | $J = f(W)$ | $q = f(T)$ (Fig. 8) |
| Initial conditions | W = 26 % | T = 26°C |

*where: W - humidity; T - temperature; k - coefficient of thermal conductivity of the material;* $\rho_0$ *- density of dry material [kg m*$^{-3}$*]; c - specific heat capacity [J kg*$^{-1}$ *K*$^{-1}$*]; λ - heat transfer coefficient of the material;* $\lambda = \frac{k}{\rho * c}$, $\rho * c = const$ *D - diffusion coefficient ; E - modulus of elasticity ; ν - Poisson coefficient ; MOR - Modulus of rupture; α - coefficient of deformation; J- mass flow; q - heat flow*

a reduced coefficient of thermal conductivity k, c, which is used to model the diffusion coefficient (Table 1); modulus of elasticity and Poisson's ratio.

The characteristics of the real and fictitious material used in the analogy are taken from a literature source [8]. Fig. 2 shows the dependence of the thermal conductivity coefficient (modeling the diffusion coefficient) on the temperature at the points of the brick volume. Fig. 3 and Fig. 4 show the dependence of the mechanical properties of the material (modulus of elasticity E and Poisson's ratio) on temperature.

Because the material used is too brittle to perform pure tensile experiments, its strength is determined by bending experiments in which the so-called MOR (modulus of rupture) is obtained. Fig. 5 shows the temperature dependence of this characteristic.

Since cracks in the material result from uneven shrinkage during the drying process, the coefficient of thermal expansion modeling the coefficient of deformation is one of the main characteristics of the analogy. Fig. 6 shows the temperature dependence of this characteristic in the two phases of drying - from T = 0°C to T = 8.2°C (W = 8.2 %) and above this limit.

Table 2. Material characteristics.

| Name | Dimension | Value |
|---|---|---|
| Density of wet material | kg $m^{-2}$ | 2124 |
| Density at critical humidity | kg $m^{-2}$ | 2189 |
| Average density | kg $m^{-2}$ | 2113 |

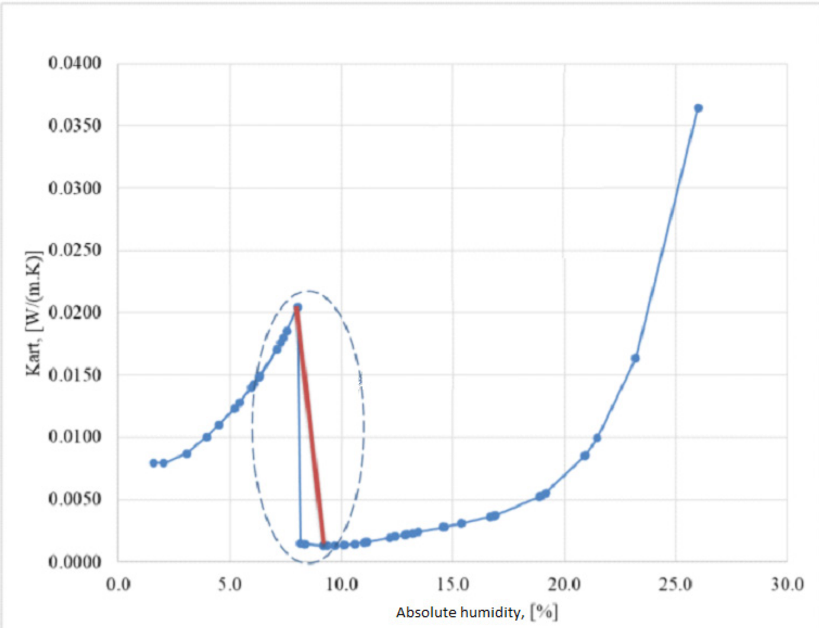


Fig. 2. Change of the artificial coefficient of thermal conductivity with the absolute humidity of the material [8].

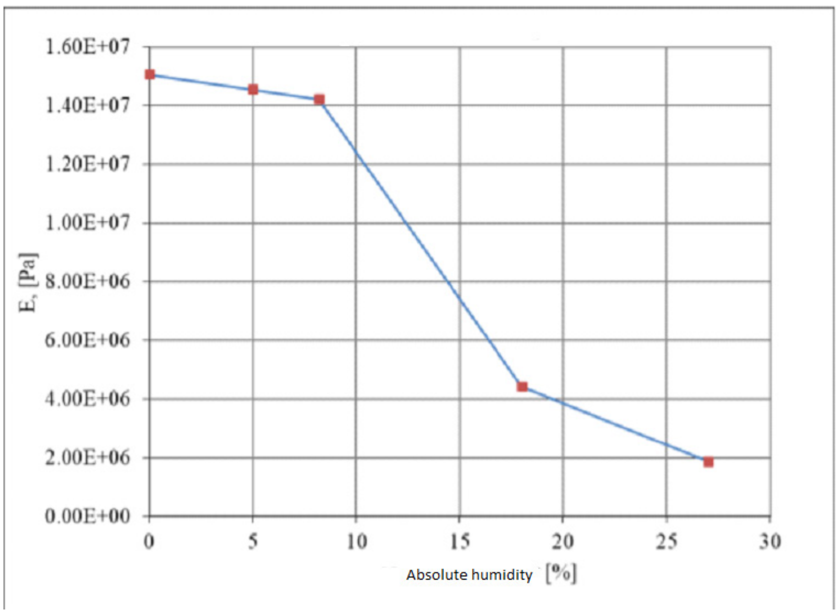


Fig. 3. Modification of the modulus of elasticity with the moisture content of the raw material [8].

The boundary conditions reflect the mass flow through the surrounding surface of the brick except for the bottom surface on which it lies and where the mass flow is zero. In the analogy, the mass flow is replaced by heat flow, whose dependence on temperature (modeling humidity) is shown in Fig. 7.

The analysis was conducted in two parts. The first part is realized with the module "Transient Thermal", and through the thermal analysis, the process of diffusion of water from the brick material during drying is modeled. For the purposes of the study, an initial temperature T = 26°C was set, modeling humidity of W = 26 %.

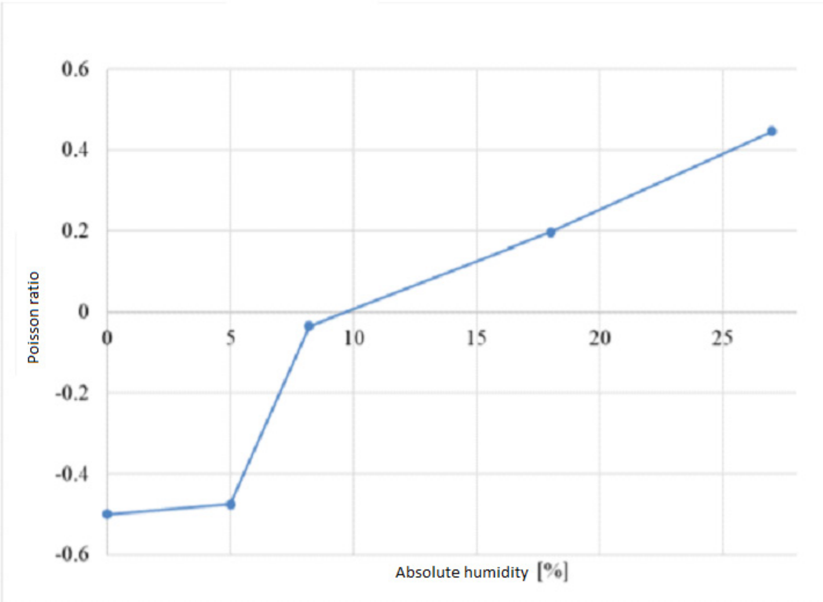


Fig. 4. Change of the Poisson's ratio with the moisture content of the raw material [8].

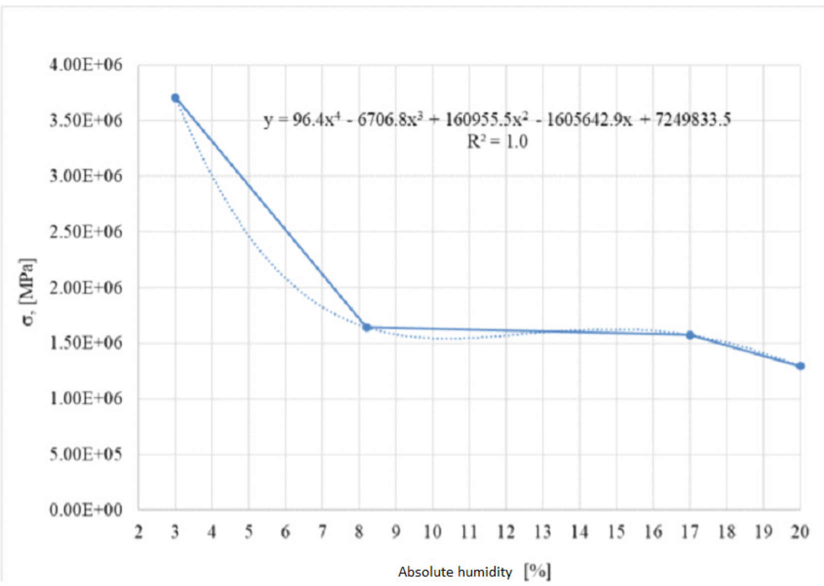


Fig. 5. Change of the bending strength with the moisture content of the raw material [8].

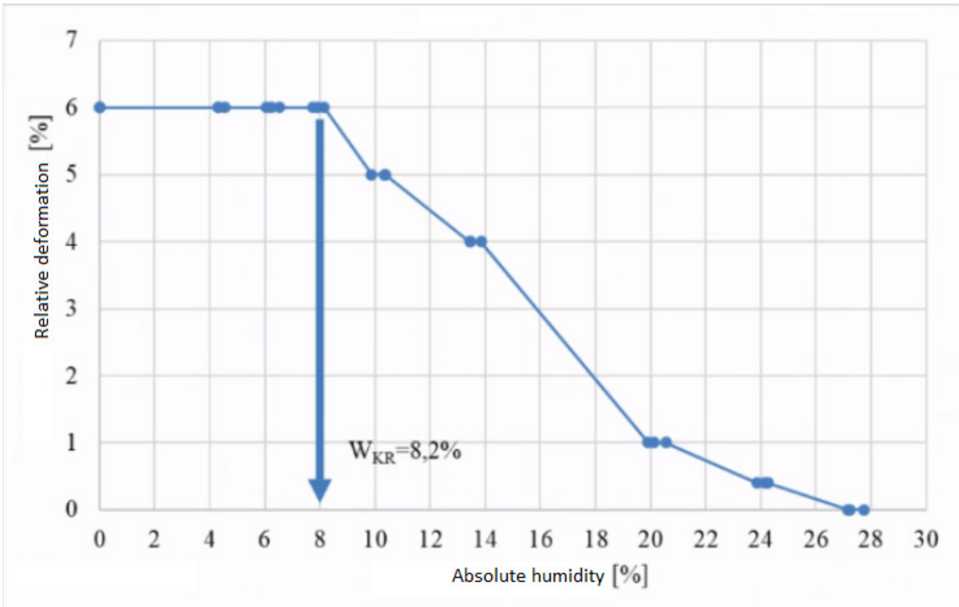


Fig. 6. Change of the deformation with the moisture content of the raw material [8].

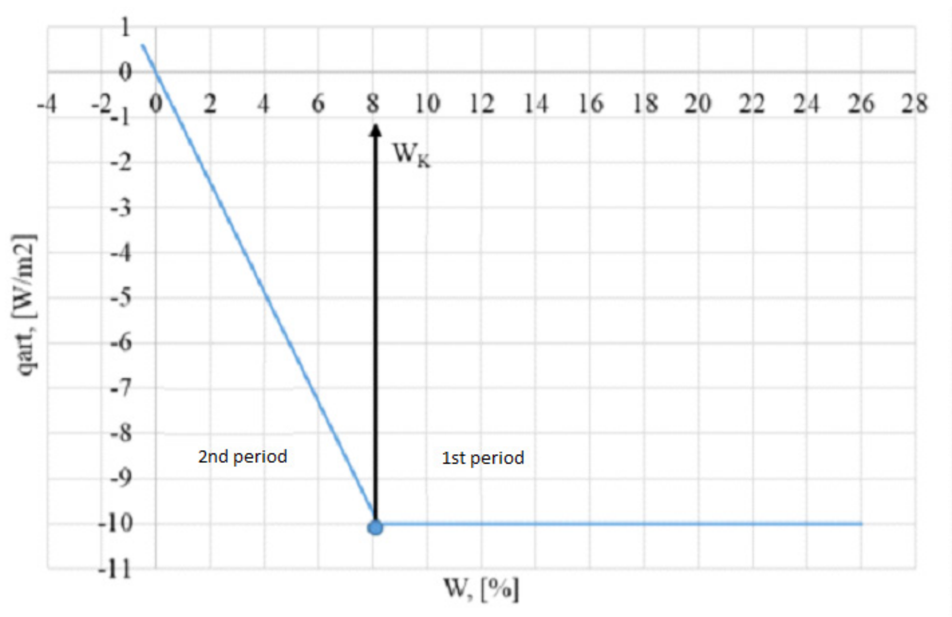


Fig. 7. Change of the artificial heat flux density with absolute humidity Change of the bending strength with the moisture content of the raw material [8].

The emission of moisture in the drying process is set as heat flux q = 10 W m $^{-2}$ during the first 5.6 h gradually decreasing to q = 3 W m $^{-2}$ in 7 h.

Results for the temperature distribution in the volume of the material corresponding to the humidity in the actual drying process were obtained from the analysis.

These results were used as initial conditions in the second part of the analysis realized with the module "Static Structural". The moment of the drying process at which there is the greatest temperature difference is selected. Temperature stresses are calculated with this temperature difference. In the calculations, the kinematic immobility of the object is ensured by fixing the displacements of three points not lying on one line. The area where the temperature differences cause the greatest stresses was chosen for the analysis of the crack formation. A crack was introduced in this area and the stress intensity factor K1 (of opening) at different crack orientations was calculated. The analysis was performed using the Fracture function of the ANSYS Workbench Mechanical software with a crack of the Semi-Elliptical type (Crack), located in the zone of maximum tensile stresses.

The different orientation of the crack is set by changing the angle of the crack front relative to the axes of the global coordinate system (angle $\varphi$ in Fig. 8).

Based on the values of the intensity factor and the angle of orientation, the initialization of cracking and the crack propagation in the drying process in the production of ceramic products can be estimated.

## RESULTS AND DISCUSSION

Fig. 9 shows the result obtained for the distribution of the temperature in the volume of the material corresponding to the humidity in the actual drying process. The mathematical model of thermal conductivity allows us to obtain negative temperatures, which contradicts the nature of the drying process. This effect is eliminated in the solid-state analysis with an appropriate coefficient of thermal expansion.

In the linear formulation of the problem, the areas with the greatest temperature difference correspond to the areas with the greatest temperature stress (Fig. 9).

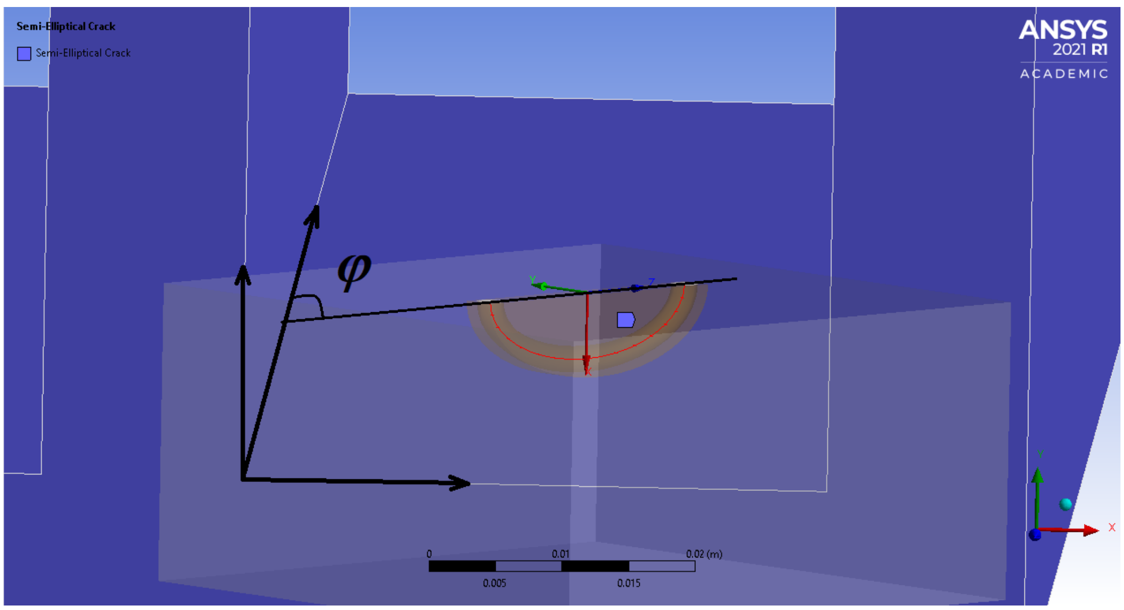


Fig. 8. The angle $\varphi$ of the crack front relative to the axes of the global coordinate system.

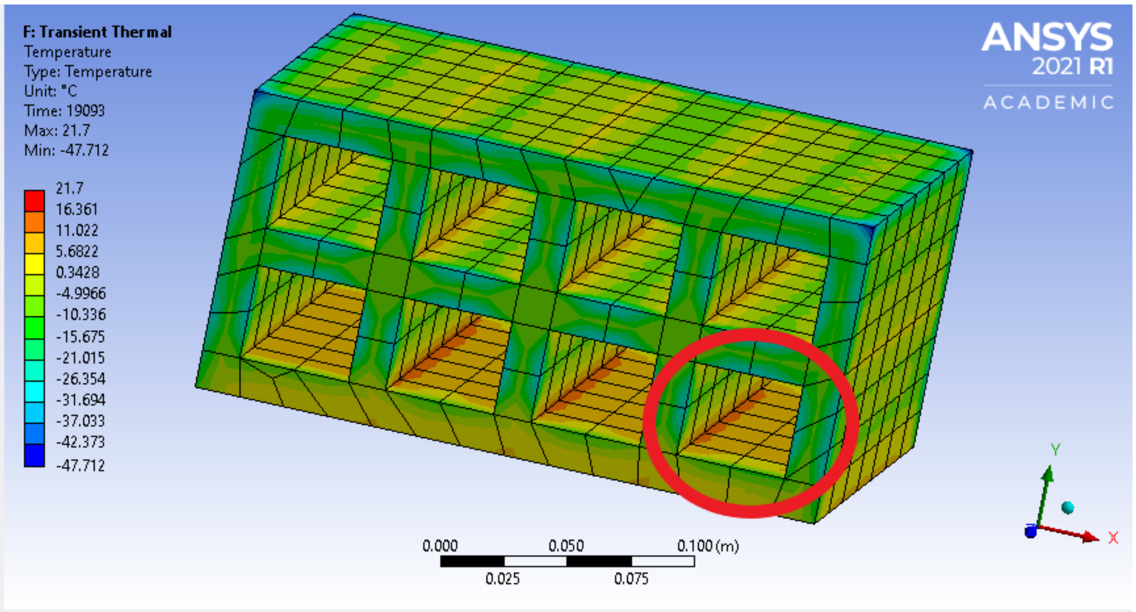


Fig. 9. Result obtained for the distribution of the temperature in the volume of the material corresponding to the humidity in the actual drying process.

Fig. 10 shows the obtained values for the stress intensity factor K1 for a crack located in the area with the largest temperature differences in the model and oriented $\varphi = 90^o$.

For the actual drying process, these values will be responsible for a crack located in the area with the greatest deformations from shrinkage of the material during drying.

From the point of view of the technological process, in addition to the place where the crack is most likely to be initiated, its probable orientation is also important. A conclusion about this orientation can be made on the basis of K1 (higher value of K1 - higher probability of crack initiation).

Fig. 11 shows the values of the stress intensity factor at different crack orientations. It can be concluded for the case under consideration that the probable orientation of the crack will be at $\varphi = -20^o$ (respectively $-160^o$).

## CONCLUSIONS

Estimation of the probability of occurrence and development of cracks in the drying process in the production of ceramic products can be successfully done using an approach that combine the fracture mechanics and temperature-diffusion analogy. The basis of the temperature-diffusion analogy is the correspondence between humidity and temperature in the resolving equation of the two processes. These equations can be successfully solved with the help of the "Transient Thermal" and "Static Structural" modules of the ANSYS Workbench software. To implement the solution, it is necessary to know the mechanical properties of the material (coefficient of the thermal conductivity and diffusion coefficient), as well as the boundary conditions of the process (mass and heat fluxes). The obtained results for the temperature distribution show the picture of the moisture content in the real drying process. Results for deformations and mechanical stresses in the material can be obtained. By introducing a crack and applying the techniques of fracture mechanics, the values of the stress intensity factor at different crack orientations can be obtained. These values indicate the

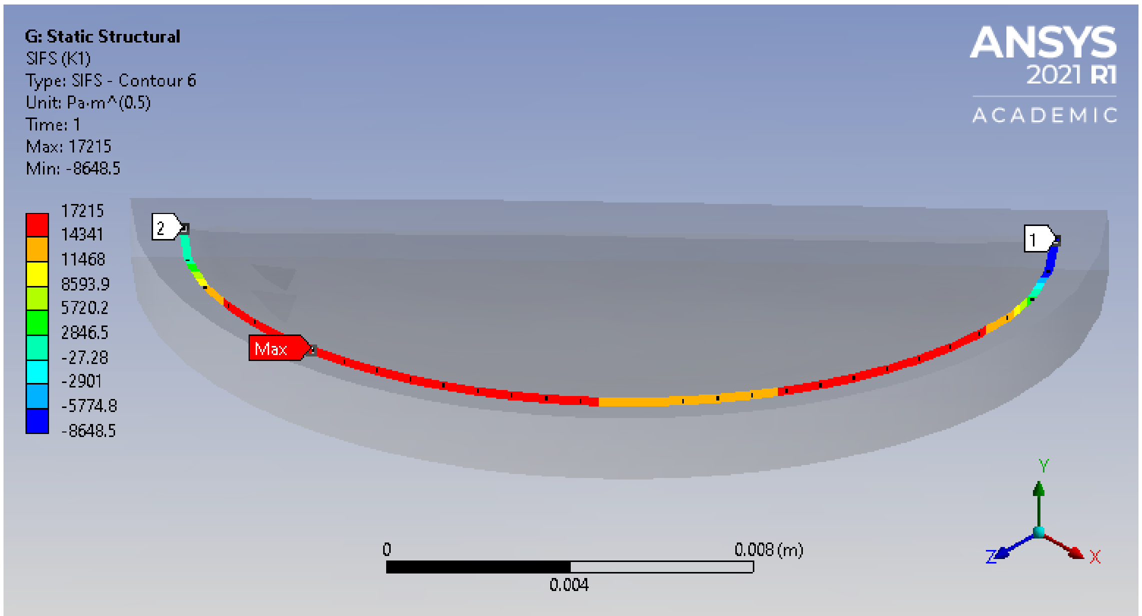


Fig. 10. Obtained values for the stress intensity factor K1 for a crack located in the area with the largest temperature differences in the model and oriented $\varphi = 90^{o}$.

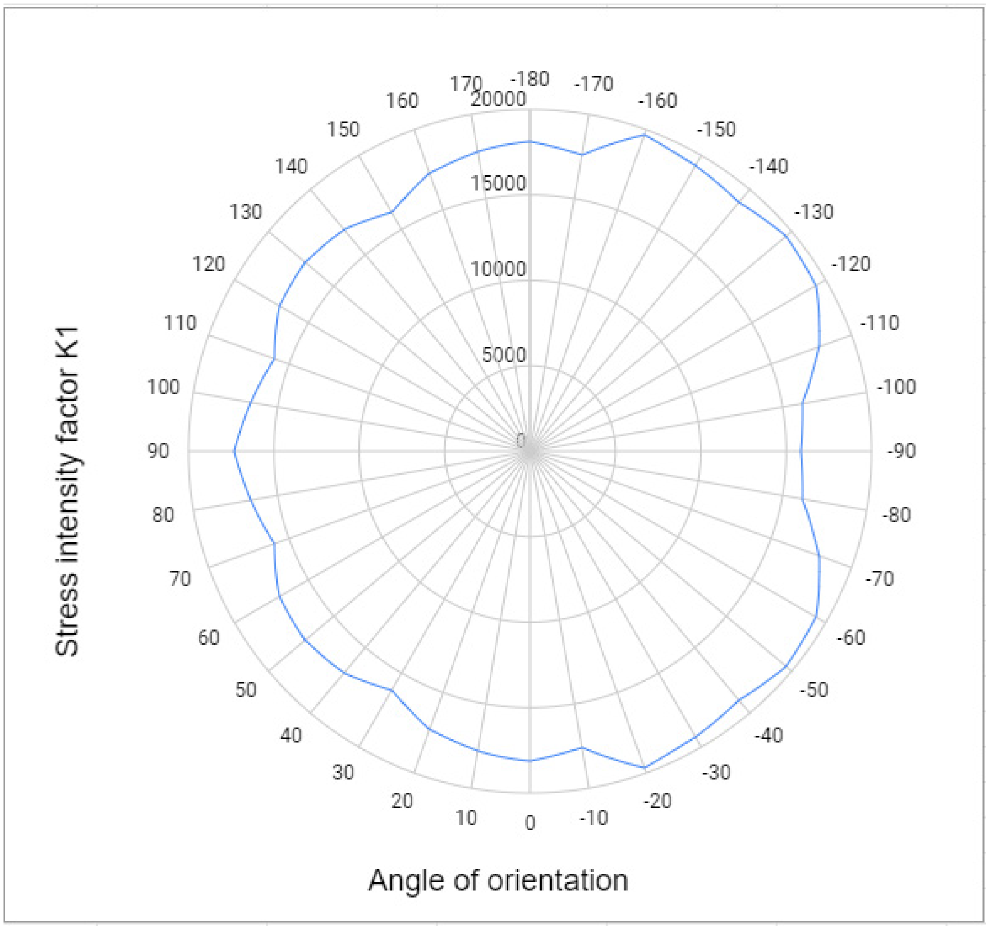


Fig. 11. Values of the stress intensity factor at different crack orientations.

probability of crack propagation. In the case under consideration, the results show that the probable orientation of the crack is at $\varphi = -20^{o}$ (respectively $-160^{o}$).

**REFERENCES**


1. S. Nevenkin, Drying and Drying Techniques, Technika, Sofia, 1985, (in Bulgarian),
2. A.V. Lykov, Theory of Drying, Moscow, 1968, (in Russian).
3. Fick's Second Law of Diffusion, LibreTexts, CXone Expert knowledge management, 2022, https://eng.libretexts.org/Bookshelves/Materials_Science/TLP_Library_I/20%3A_Diffusion/20.02%3A_Fick's_Second_Law_of_Diffusion.
4. N. Perez, Solution of Fick's Second Law, Electrochemistry and Corrosion Science, Springer International Publishing Switzerland, 2016, DOI 10.1007/978-3-319-24847-9.
5. A. Sander, D. Skansi, N. Bolf, Heat and mass transfer models in convection drying of clay slabs, Ceramics International, 29, (6), 641-653, 2003.
6. ANSYS Release 16, Theory Reference © SAS IP, Inc., 2016.
7. N. Penkova, P. Chervenliev, B. Mladenov, K. Krumov, Mathematical Modeling and Numerical Simulation of Coupled Mass Transfer and Mechanical. Processes in Ceramic Ware at Industrial Drying. Universal Journal of Mechanical Engineering, 7, (4), 2019, 231-239.
8. B. Mladenov, Efficient Drying Regimes for Bodies with Complex Geometry, Ph.D. Thesis, University of Chemical Technology and Metallurgy, Sofia, 2021, (in Bulgarian).