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Description of heat flow in a surgical cement layer

JERZY OKRAJNI, SYLWIA ZIEMBA, JULIAN STUMPF

Silesian University of Technology, Department of Mechanics of Materials

The hip joint alloplasty is one of the surgical treatments often performed in clinics and in trauma-orthopaedic departments of hospitals. The popular method for connecting pelvis and femoral component with a bone during alloplasty is the use of a thin surgical cement layer. During a surgery, thermal properties of the cement, e.g., high polymerization temperature, appear to be harmful. The understanding of thermodynamic phenomena occurring during polymerization process is necessary to limit harmful cement influence on human body. Thus the description of the heat release due to chemical reactions is especially important. The paper deals mainly with the description of the heat source and temperature field in the surgical cement layer. Characteristics of the heat source in the cement were described. The temperature distributions in the cement layers at different values of thermal diffusivity coefficient were presented.

1. Introduction

Methyl polymethacrylate, called by doctors a “surgical cement”, is still one of the biomaterials commonly applied in medicine. Many years have passed since first tests on the cement were carried out and a number of studies can be found in the literature, enumerating both advantages and disadvantages of this material [1]–[4].

Surgical cement is composed of the molecules of methyl ester polymer and acrylic acid. It is mixed with a liquid monomer and undergoes polymerization. During polymerization, surgical cement has a sticky fluid consistency, so it can be freely shaped. Currently, this material is frequently applied to fix implants. Cements are also used to fill in bone losses, as the material for spacing components which enable the shape of damaged bone to be maintained for some time. They are applied in neurosurgery as well [1], [3]. The main problem connected with the application of the cement in surgery is a high temperature during its polymerization, which induces tissue necroses [1]–[5]. Therefore, in many research centres the studies on improving the functional properties of surgical cements are undertaken. These studies have been conducted for many years in order to obtain the desirable combination of various and often reverse properties of cements, including their viscosity and a high temperature of polymerization, these being of the essence during a surgical procedure, as well as their mechanical properties, including fracture toughness.

The research has been mostly focused on the chemical reactions that take place during polymerization. A number of studies have also been undertaken to discuss the influence of the boundary conditions which determine the heat exchange process on the surface of a polymerizable cement and their influence on a durable incorporation of this material into the living structure of tissues in an organism, these most often being bone tissues. So far, the phenomenon of heat exchange on the boundary of cement and bone tissue has been described in a rather sufficient manner. New cements of a lowered polymerization temperature have been developed, but it is still too high, which poses a serious problem to surgeons. Possible reduction of the adverse cement effect on human organism requires an in-depth understanding of the polymerization process in terms of thermodynamics. The problem of an accurate description of the heat source, being the effect of a chemical reaction, is of particular importance, since its time characteristics determine the intensity of polymer effect on human organism.

This paper focuses on the description of the source temperature field in a surgical cement film. It presents the results of measurements which allow the determination of the characteristics of the internal heat source in cement. The paper describes the temperature field in a surgical cement plate, determined for different values of thermal diffusivity coefficient. It is focused on testing the cements applied in endoprosthesoplasty of the hip joint.

2. Temperature field in a cement layer during polymerization

Endoprosthesoplasty of the hip joint is one of the most frequently performed surgical procedures in clinics and at casualty-orthopaedic wards in hospitals. The procedure consists in replacing a diseased joint with artificial elements called endoprostheses, made up of the parts fastened in a hip and in a femur. The part that replaces the diseased or defected acetabulum consists of elements whose external surface has a form of a spherical cap. Its concave surface cooperates with a spherical head of the femoral part, i.e. the so-called stem. In order to fix the femoral component and the hip component they are frequently connected with the bone tissue by means of a thin film of surgical cement. Such a solution has been applied for many years now and still remains one of the basic methods of fixing the implants whose durability in this case depends to a large extent on the properties of the polymer layer formed during a surgical procedure.

The paper presents an analytical description of the heating process of a surgical cement film during its polymerization. Due to a small thickness of the cement layer compared to the dimensions of a section of endoprosthesis stem and its length as well as to the dimensions of the hip component, a layer model in the form of an infinitely vast plate has been assumed. Assuming that the conditions on each of the external surfaces are homogeneous, the temperature at the section of such a plate depends on one coordinate *x*, which represents the distance of a point from the symmetry plane. Thus, the temperature field can be described by the equation:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c_p} \frac{\partial^2 T}{\partial x^2} + \frac{q_v}{\rho c_p}, \tag{1}$$

where ρ means the density, c_p is the specific heat, and q_v is the efficiency of the internal heat source referred to a volume unit. Complexity of the analytic solution of equation (1) depends on the boundary conditions assumed. A method of determing the temperature distribution in a plate with symmetrical boundary conditions on both external surfaces is presented in the paper [6]. It has been assumed that for an initial instant $t = 0$, the temperature distribution throughout the plate volume is uniform and the temperature amounts to T_0. The temperature of the plate surface remains constant with time and equals T_p. Under initial and boundary conditions assumed in such a way the solution of equation (1) can be presented in the form:

$$T = T_p + \sum_{i=1}^{n} A_i(t) \cos\left(\delta_i \frac{x}{b}\right). \tag{2}$$

In this equation, the coefficients $A_i(t)$ are determined as follows:

$$A_i(t) = \frac{2\,(-1)^{i+1}}{\delta_i}\, e^{-\delta_i^2 a \frac{t}{b^2}} \left[(T_0 - T_p) + \int_0^t e^{\delta_i^2 a \frac{t}{b^2}} D(t)\,dt \right], \tag{3}$$

where $\delta_i = \frac{2i-1}{2}\pi$, $a = \frac{\lambda}{\rho c_p}$, $2b$ is the plate thickness.

The time function $D(t)$ occurring in equation (3) is combined with the heat source efficiency:

$$D(t) = \frac{q_v}{\rho c_p}. \tag{4}$$

3. Characteristics of internal heat source

Lack of available data induces us to conduct our own experiment. Variable temperatures of samples of a material during polymerization were investigated. Because the experiment was aimed at limiting the heat exchange phenomenon, it was performed in a vacuum. For the examination, surgical cement, called Simplex, was used: 40.0 g of PMMA powder was combined with 20.0 cm^3 of MMA fluid. From this cement the samples were prepared. The cement was stirred and applied under vacuum conditions (the pressure in the order of 10^4 Pa). The cement was poured into a thin polypropylene mould, and then its temperature was measured with the thermocouple K placed in the middle of the cement substance (figure 1). The dependence $T(t)$ was then approximated with the function:

$$T = A\left(1+\frac{2}{\pi}\arctan\left(\frac{t}{B}-C\right)\right)+C\,. \qquad (5)$$

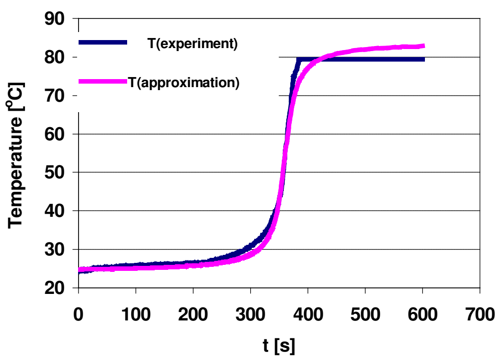

Fig. 1. Dependence of temperature on time determined for a cement sample during polymerization process in vacuum

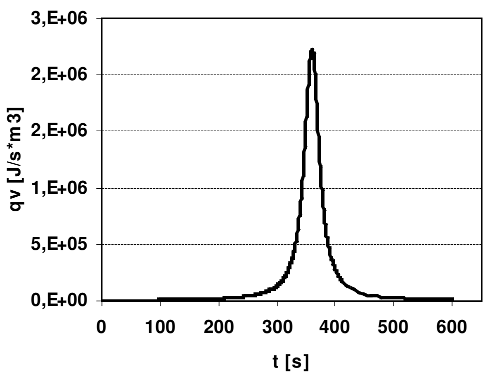

Fig. 2. Characteristics of internal heat source effectiveness during polymerization process

The constants A, B and C were determined and the following relationship was obtained:

$$T = 30\left(1+\frac{2}{\pi}\arctan\left(\frac{t}{15}-24\right)\right)+24\,, \qquad (6)$$

where, due to the system of units assumed when determining the constants A, B and C, the time is to be expressed in seconds, whereas the temperature T, in °C. The derivative of the approximating function (6) was determined:

$$\frac{dT}{dt} = D(t) = \frac{q_v}{\rho c_p} = \frac{2A}{B\pi\left(1+\left(C-\frac{t}{B}\right)^2\right)}. \tag{7}$$

Based on the literature data [7], it was assumed that

$$\rho c_p = 1.75 \cdot 10^6 \ \frac{\mathrm{J}}{\mathrm{m^3\,K}}.$$

The characteristics of the intensity of a volumetric heat source determined in such a way is presented in figure 2.

4. Temperature distributions in a plate made of surgical cement

The properties of surgical cement have been the subject of numerous studies. Particular attention was devoted to its mechanical properties, which have been extensively described, whereas the data concerning its thermal properties are seldom available or given for wide ranges. They may differ, depending on the additives applied, e.g., antibiotics, fillers of contrasting agents [2], [5], [7]–[11]. In the study, the values of the thermal diffusivity coefficient *a* were assumed in the

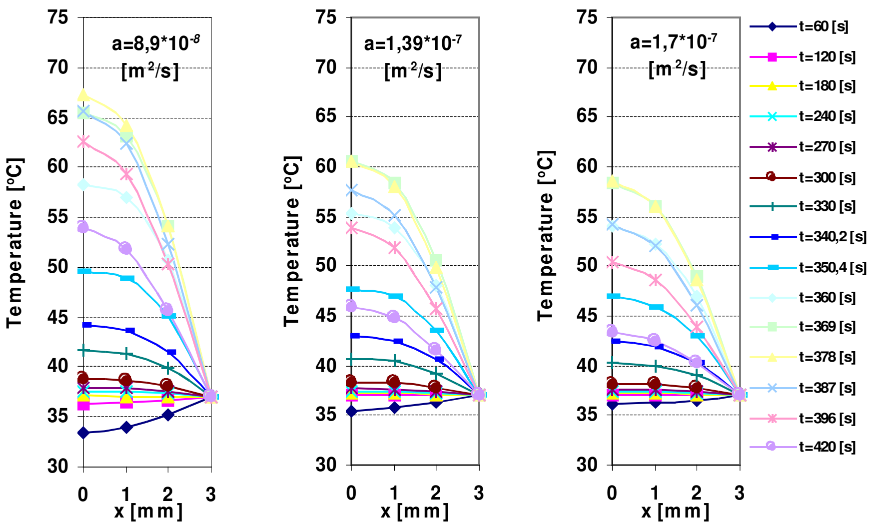

Fig. 3. Temperature distributions on a plate section at different values of thermal diffusivity coefficient

range of $8.9 \cdot 10^{-8}$–$1.7 \cdot 10^{-7}$ [m^2/s] [7]–[9]. Based on equations (2)–(4) and (7) the temperature distribution in the plate was determined. A constant temperature of the plate surface T_p was assumed to be 37 ºC, which corresponds approximately to the human body temperature, while the plate initial temperature $T_0 = 24.8$ °C.

The thickness of the cement layer assumed was 6 mm. At the assumed values of thermal diffusivity coefficients, the temperature distributions were determined in the cement layer in different instants, counted from the moment of cement application. Calculations were made for instants ranging from 0 to 420 s. After the time of 420 s full polymerisation of the cement took place (figure 1). The results of the calculations are presented in figure 3.

Due to the symmetry of boundary conditions the figure shows temperature distributions on one side of the symmetry plane; coordinate $x = 0$ mm corresponds to the points on the plate's symmetry plane, whereas coordinate $x = 3$ mm represents the plate surface. The maximum temperature of the plate centre differs in the value of thermal diffusivity coefficient.

5. Temperature measurements during cement polymerization

Figure 4 shows the curves of the dependence of temperature on time plotted for the points in the plate's symmetry plane at different values of the coefficient a. The curves presented in figure 4 show a significant reduction of the maximum temperature with an increase in the thermal diffusivity coefficient. An approximately double increase in this coefficient was responsible for the reduction in the maximum temperature, approaching 10 °C, in the model of cement layer.

The calculations done show that the influence of the physical properties of cement film that characterise the heat flow phenomenon on the temperature of this film can be described qualitatively. In material engineering, the model formulated in such a way can be used to forecast the properties of surgical cements as composite materials, whose physical properties are modelled by selecting the type and volume fraction of particles added to them [1], [8].

Experimental research was conducted by adding cement of the trade name Simplex, in the form of a sticky fluid, to wooden moulds specially prepared. The moulds allowed the preparations to be formed as cement plates, 40×60×6 mm. From the technical viewpoint such a plate can be considered to be approximately infinitely vast. In the middle of each mould, an hole of ∅ 0.5 mm was made, in which a thermocouple J was placed with a wire of 0.25 mm in diameter, reaching the half of the cement layer thickness, i.e., the plate's symmetry plane. The cement was stirred manually to become a homogeneous substance, and then was poured into the moulds. The moulds were immersed in a water bath of a temperature of about of 37 °C, which corresponds to the human body temperature. The temperature was recorded as a function of time to determine the heat source characteristics. The results obtained are presented in figure 5.

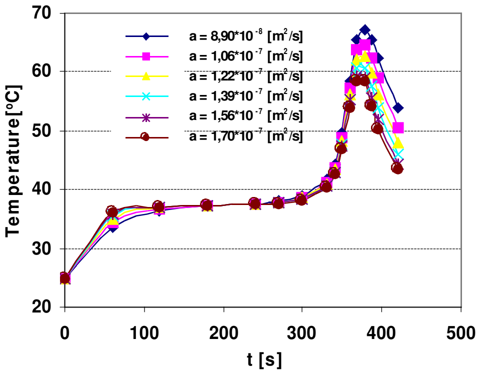

Fig. 4. Temperature at the points in the plate symmetry plane versus time (calculations)

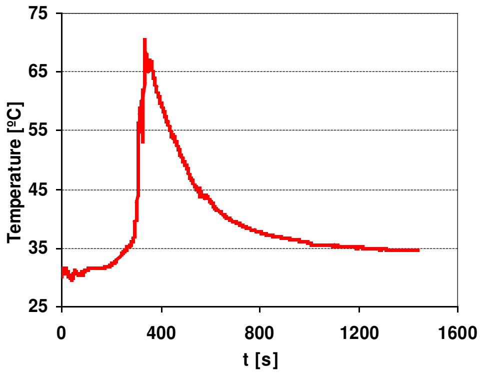

Fig. 5. Temperature versus time during cement polymerization in water bath (measurements)

6. Conclusions

Although the data concerning the basic physical properties occurring in equations (2) and (3) are available in the professional literature, we still face a significant problem of to how to determine the heat source characteristics when describing the time-dependent temperature distribution in polymerizing cement. The examinations made allow us to confirm a similar nature of temperature changes as a function of time in the case of the plate tested when referred to the calculation results. In qualitative terms, this corroborates the correctness of the model approach applied. Nevertheless, there is still a need to continue the verification research for the purpose of confirming the model and experiment compliance at different boundary conditions and different material properties.

The developed model of the heat flow process, applied in order to assess the temperature distribution in a surgical cement layer, represents the nature of thermal phenomena taking place during its polymerization. Based on the model developed, one can, inter alia, evaluate the influence of the thermal diffusivity coefficient a on the maximum temperature of cement during polymerization. By combining the value of the coefficient a with the volume fraction of the components added to polymer, it is

possible to evaluate the direction of changes caused by the components added, e.g., Al_2O_3, as well as to estimate the maximum temperature for their volume fractions given.
In this way, the approach presented can be applied in designing the polymer composites. Finally, the method allowing improvement of cement properties should be verified experimentally. Thus, our examinations constitute the first stage of research that attempts to describe analytically the thermal phenomena taking place during polymerization and the results of investigations necessary to calculate the characteristic parameters of the heat source.

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