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Investigation of cyclic creep of surgical cements

A. Balin*, G. Junak
Department of Materials Mechanics, Silesian University of Technology,
ul. Krasińskiego 8, 40-019 Katowice, Poland
* Corresponding author: E-mail address: alicja.balin@polsl.pl

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ABSTRACT

Purpose: The paper suggests to adapt the research method of low cycle fatigue for modelling the loads and deformation on surgical cements in an artificial hip joint. Surgical cements have also been modified in order to improve their functional properties.

Design/methodology/approach: Low cycle fatigue tests were conducted on samples made from Palamed cement without an addition and on samples made from cement modified with glassy carbon and titanium. The tests were conducted on a servohydraulic fatigue testing machine, MTS-810, with load control.

Findings: Fatigue tests proved viscoelastic character of all the tested materials. During the fatigue tests the phenomenon of cyclic creep was observed.

Research limitations/implications: Modelling the loadings and deformations of cement in endoprostheses of joints with the low cycle fatigue method takes into account its all high value, while cement is being used for endoprostheses for many years in the conditions of random stress and deformation courses. Therefore the obtained deformation values are bigger than those which would have been obtained in real conditions in the same time.

Practical implications: The low cycle fatigue tests carried out showed how important is the factor of time for the behavior of surgical cement in the conditions of changeable loadings. This fact is essential to assess its usability for endoprosthesoplasty of joints. The stem subsidence and remodeling of bone occurred in the course of the cement deformation. For the clinical practice the estimation of the deformation value of the cement and stem subsidence during the exploitation of the artificial hip joint is the important problem.

Originality/value: The rheological phenomena in surgical cements, which is viscoelasticity material, occurred at low cycle fatigue tests. The deformation increase in the conditions of the cement creep is the fundamental phenomena.

Keywords: Fatigue; Biomaterials; Mechanical properties; Modelling

PROPERTIES

1. Introduction

As polymer composites, bone cements are biomaterials that have been used for a few dozen years to fix human joints' endoprostheses, as well as in many other surgical procedures consisting of defective bone tissue substitutions. At present, despite numerous constructional solutions regarding endoprostheses, endoprosthesoplasty with the use of cement is still one of the basic procedures in surgical treatment of joints [1-3].

Long-term artificial joint stability, often identified with durability as one of the prerequisites for the anticipated biofunctionality, is determined by material, geometric and dynamic properties (load) of the endoprosthesis' structure and its coupling with the human organism [4]. The most often implanted joint is the hip joint, being under the greatest load in the human organism. Bone cement is a very important component in an artificial hip joint, since after setting, it bonds the endoprosthesis with the bone [3]. Thus, the properties acquired by the surgical cement through time in the conditions of variable loads influence on the biomechanical durability of an artificial hip joint.

Durability of the artificial hip joint, especially in the case of cement anchoring of endoprosthesis components, depends to a large extent on rheological processes, in particular creep and relaxation. Surgical cement, being a polymer composition, in a model approach represents a classical example of a viscoelastic substance [5-13]. The bone can be also regarded as a viscoelastic material [14,15]. The physicochemical and mechanical properties of such materials change with time, as is shown by rheological equations. For instance, the so-called equations of state have the form:

$$F(\sigma_{ij}, \varepsilon_{ij}, T, t) = 0 \quad (1)$$

where:
σ_{ij} – stress tensor,
ε_{ij} – strain tensor,
T – temperature,
t – time.

In connection with the rheological properties of the bonds made of materials which anchor the endoprosthesis in the femoral bone channel, the problem of the artificial hip joint's durability evaluation is complex. It should be also emphasized that the ranges of scale regarding the differences and scope of the destruction phenomena present in the biomechanical bonding, when compared to decohesion in technical materials or destruction of technical objects, is so large that adoption of the methods applicable in the field of material mechanics to such evaluation obliges the researchers to a particularly thorough analysis and interpretation of its results.

From among many properties of surgical cement, which influence the durability of cement endoprosthesoplasty, the most important for a clinical verification are those which directly depend on the action of cyclic loads, both in a short- and a long-term period [16]. In a 24-hour period, there are periods of both physical activeness and periods of rest in a typical patient. They are connected with variable characteristics of load imposed on the joint and the cement inside it, the latter being one of the joint's components [10,11,17-19]. The phenomenon of cement degradation during the person's movement takes place under the action of cyclic changes of loads of high values. Therefore, they can be defined with high probability as fatigue in the range of a small number of cycles. Bearing this in mind, the authors have made an evaluation in this paper of cement behaviour in an artificial hip joint, applying the low-cycle fatigue testing method .

A viscoelastic material which, when having the freedom of dislocation, creeps under cyclic load, will relax with a limited degree of freedom in dislocation. Surgical cement's susceptibility to cyclic creep during fatigue loading of samples has been experimentally shown in this study.

2. Materials and method

The material for the research was surgical cement of the manufacturer's name Palamed 40, used in clinical practice, and the same cement with additions of glassy carbon in the form of powder of 10-160 μm granulation and titanium particles of a size in the range of 25-150 μm. These materials (carbon and titanium) have found an application in medicine [20-25]. The mass fraction of the additions amounted 3.2%. Such methods of physical modification of a PMMA-based (methyl polymethacrylate) cement were applied for the purpose of reducing its shrinkage and high temperature in the polymerization process.

The tests were conducted on a servohydraulic machine, MTS-810, with load control. The machine is equipped with a digital control system, TestSTAR II. In order to ensure precise collection of all values of force and deformation, the tests were carried out using the TestWARE SX programme. A change of load was modelled with a triangular cycle of 0.3 Hz frequency and maximum force equal 1500 N (Fig. 1). A method of cyclic loading of the samples was assumed which induces variable stresses in the area of tensile stresses – the most disadvantageous for cement, since they lead to its cracking and chipping [26-30]. The maximum values of those stresses reached a value equal 25.8 MPa, i.e. ca. 90% of cement's tensile strength R_m [31,32].

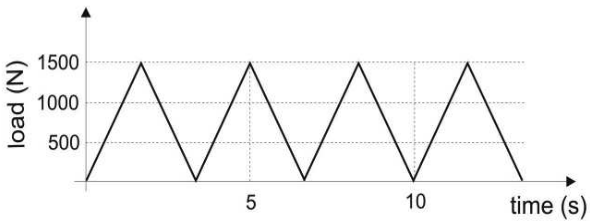

Fig. 1. Loading cycle in low cycle fatigue tests

During the tests, diagrams were recorded of load (stress) dependence on deformation of a sample with an increasing number of cycles N. The measurement of the deformation was performed using an extensometer with a 25 mm base. For all samples of cement without an addition as well as those modified with glassy carbon or titanium, the recorded dependencies of load change on deformation had the nature of a hysteresis loop, which can be explained by the nature of viscoelastic behavior of the material.

During the investigations, a phenomenon of cement's cyclic creep was observed, manifesting itself in the hysteresis loops' displacement (deformation growth) and in their angle inclination reduction with an increasing number of cycles. The tests were conducted until samples' failure, obtaining the durability values, N_f. Based on the research results, it was found that the durability values N_f cannot account for a sufficient criterion in the evaluation of the cements tested due to the random nature of cracking of samples containing pores inside. In the paper, an attempt was undertaken to compare the investigated materials on the basis of the hysteresis loop's inclination angle after a specified number of cycles, N, the same for all samples. Changes in the hysteresis loop's inclination describe the variability of the dynamic module with an increasing number of cycles. The test results along with calculated values of the dynamic elasticity modulus after a number of cycles amounting to: 1, 1000, 2000, 3000 and 4000, respectively, for pure cement and for the modified cement are presented in figures from 2 to 4. The change in the dynamic modulus of elasticity with a growing number of cycles N for pure cement and for cement modified with glassy carbon and titanium is presented in Fig. 5.

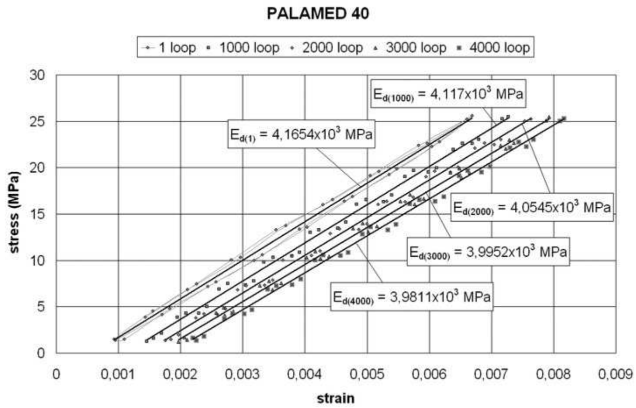

Fig. 2. Histeresis loops after a different number of cycles with the dynamic elasticity modulus values, E_d, for the Palamed 40 cement

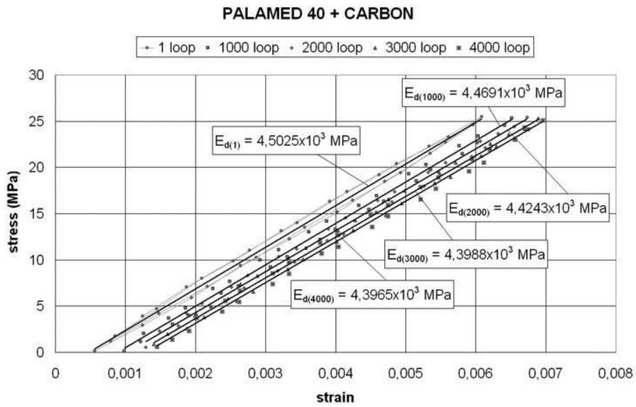

Fig. 3. Histeresis loops after a different number of cycles with the dynamic elasticity modulus values, E_d, for the Palamed 40 cement with a glassy carbon addition

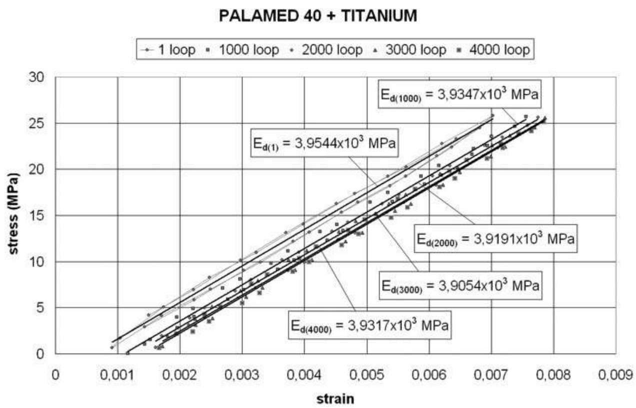

Fig. 4. Histeresis loops after a different number of cycles with the dynamic elasticity modulus values, E_d, for the Palamed 40 cement with a titanium addition

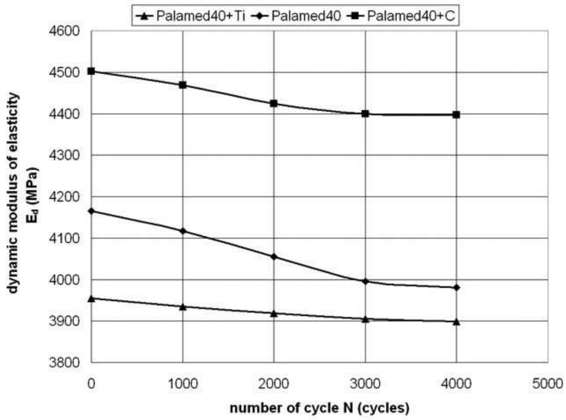

Fig. 5. The dynamic modulus of elasticity E_d changing with a growing number of cycles N for the Palamed 40 cement and Palamed 40 cement with admixtures (C - glassy carbon, Ti – titanium)

3. Conclusions

Under low-cycle fatigue load conditions, the phenomenon of cyclic creep occurs in cement, the latter being a viscoelastic material. Cement deformation caused by creep may be accompanied by subsiding of the endoprosthesis stem and bone remodeling, which is of particular importance to clinical practice. The total degree of prosthesis subsidence in cement after many years in use affects the durability of cement endoprosthesoplasty.

Physical modification of a PMMA-based cement, both with glassy carbon and titanium particles, reduced its susceptibility to cyclic creep. A reduction of the creep phenomenon was observed in particular for the Palamed 40 cement with a titanium addition. The dynamic modulus of elasticity for this material after 4000 cycles underwent very insignificant changes.

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