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ASSESSMENT OF FRACTURE TOUGHNESS AND MICROSTRUCTURE OF BONE CEMENTS

Bone cement used in orthopaedics (PMMA) is a viscoelastic material. Macroscopically, the cement structure is composed of aggregates in the form of polymer spheres with the dimensions of 10÷18 micrometers connected with polymerized monomer bridges. After mixing, it is initially a fluid, which then becomes increasingly viscous and hardens. During polymerization, the material is plastic and can be easily moulded and it penetrates deep into the fine trabecular structure of the bone. PMMA is characterized by low impact strength, which, in cements without fillers, reaches the level of K_C = 1.16÷5.2 kJ/m^2. This causes the material to show tendencies to crack at even a low dynamic load. A number of studies have demonstrated that PMMA tends to fragment and chip in artificial hip joints. The paper presents the investigations of the PMMA structure carried out for bone composites with implanted hip joint prostheses. The results of empirical investigations which allow for the determination of PMMA crack resistance were also presented. In order to determine crack resistance in bone cement, strength tests were carried out by means of an Inspekt Desk 20 machine manufactured by Hegewald & Peschke, equipped with a device for three-point bending. The measure of crack resistance was a critical value of the stress intensity factor K_Q. In order to compare the results, numerical calculations of the stress intensity factor (WIN) were also carried out for the three-point bending of a SENB sample made of SIMPLEX P + carbon fibre.

Keywords: **bone cement, carbon fibre, fracture toughness, numerical simulation, SENB**

OCENA ODPORNOŚCI NA PĘKANIE ORAZ MIKROSTRUKTURY CEMENTÓW KOSTNYCH

Stosowany w ortopedii cement kostny (PMMA) jest materiałem lepkosprężystym. Makroskopowo masa cementowa złożona jest z agregatów kulek polimeru o wymiarach 10÷18 mikrometrów łączonych mostkami spolimeryzowanego monomeru. PMMA może być stosowany jako materiał bez domieszek lub z wprowadzonymi wypełniaczami. Po zmieszaniu początkowo jest płynną substancją, która następnie staje się coraz bardziej lepka i twardnieje. Podczas polimeryzacji jest on plastyczny, daje się dowolnie kształtować i penetruje nawet w głąb drobnej struktury beleczkowej kości. PMMA charakteryzuje się niską udarnością, która dla cementów bez wypełniaczy ma wartości w zakresie K_C = 1,16÷5,2 kJ/m^2. W związku z tym wykazuje on skłonność do przypadkowego pękania pod wpływem niewielkich obciążeń dynamicznych. Liczne badania dowodzą, iż PMMA ma skłonność do fragmentacji i wykruszania się cementu podczas użytkowania sztucznego stawu biodrowego. W artykule przedstawiono badania struktury PMMA przeprowadzone na kompozytach kostnych z zaimplantowaną endoprotezą stawu biodrowego. Przedstawiono również wyniki badań eksperymentalnych pozwalających na określenie odporności PMMA na pękanie. W celu określenia odporności cementu kostnego na pękanie przeprowadzono badania za pomocą maszyny wytrzymałościowej Inspekt Desk 20 firmy Hegewald & Peschke wyposażonej w uchwyt do trójpunktowego zginania. Jako miarę odporności na pękanie przyjęto krytyczną wartość współczynnika intensywności naprężeń K_Q. W celach porównawczych przeprowadzono również obliczenia numeryczne współczynnika intensywności naprężeń WIN podczas trójpunktowego zginania próbki SENB wykonanej z cementu SIMPLEX P + włókno węglowe.

Słowa kluczowe: **cement kostny, włókno węglowe, odporność na pękanie, symulacje numeryczne, SENB**

INTRODUCTION

Intensive investigations of replacing human joints with artificial ones started in 1960 when Charnley implanted a prosthesis in the bone by means of methyl methacrylate. Since then, hip joint replacement has seen a great number of changes. Increasingly better methods of the development of implants allow for the creation of prostheses matching the individual conditions of patients. Individual 'replacement' components and bone cements are produced from even newer materials with very high biocompatibility and biotolerance [1]. Nevertheless, clinical practice has reported a high percentage of failures after the implantation of an artificial hip joint, caused by the loss of stability of stems in the femur, mainly due to damage to the cement mass [2].

Bone cement placed between a stem with Young's modulus E = 1,1×105 MPa and spongy bone with Young's modulus of E = 1,1×103 MPa [3] takes a great deal of responsibility for carrying the load from an isotropic stem with high rigidity to an anisotropic material with a substantially lower Young's modulus. The difference in the characteristics of the carrying load in these two centres causes high load in the bone cement and the possibility of cracking of brittle bone cement [4]. The major part of PMMAs used for orthopaedics is considerably heated during the process of polymerization. In the case of contact with a prosthesis with a considerably lower temperature at the contact surface, numerous microcracks can be observed, which, as a result of the high cyclic load, intensively increase, causing the cement mass to crack, which might lead to losing the stability of the prosthesis in the bone.

MATERIAL, METHODS AND RESULTS

Based on the empirical investigations of polymethyl methacrylate, the first implantation of a metal stem in a cow's bone demonstrated that initial microcracks are observed in the PMMA directly after the process of polymerization. The size and distribution of microcracks depends on the volume of the cement mass, which differs depending on the location of the cement implantation, both in the marrow cavity and acetabulum in the pelvis. The largest initial cracks were observed in the area of PMMA contact with the metal prosthesis. Immediately after polymerization, distinct cracks can be observed in this area, with the most probable cause being fast removal of heat by the prosthesis from the cement mass, heated as a result of an exothermic process. Additionally, polymerization shrinkage and contact with the metal stem cause a rapid reduction in temperature at the bone cement contact surface with the prosthesis, which makes the size of the cracks very dangerous (Fig. 1).

The PMMA contact surface with the bone is characterized by a very uneven structure, which results from the porous structure of the bone and PMMA penetration into the bone pores. Single dendrite fragments of PMMA show the uneven structure, also with visible microcracks inside (Fig. 2).

The empirical investigations carried out on bone composites where prostheses were implanted using PMMA and subjected to variable loads with the character and magnitude reflecting the human gait for a person with a body weight of 736 N have demonstrated that the size of microcracks dramatically increases and, during 10 years of utilization, they increase even twenty times in the area of intensive stress, which substantially reduces cement mass strength. Cement mass cracking was also observed in the samples of PMMA removed from the human body. The size and distribution of the areas where cracking was observed is clearly defined and their intensity increases with the extension of the time of use and increase in the load (higher body weight) (Fig. 3).

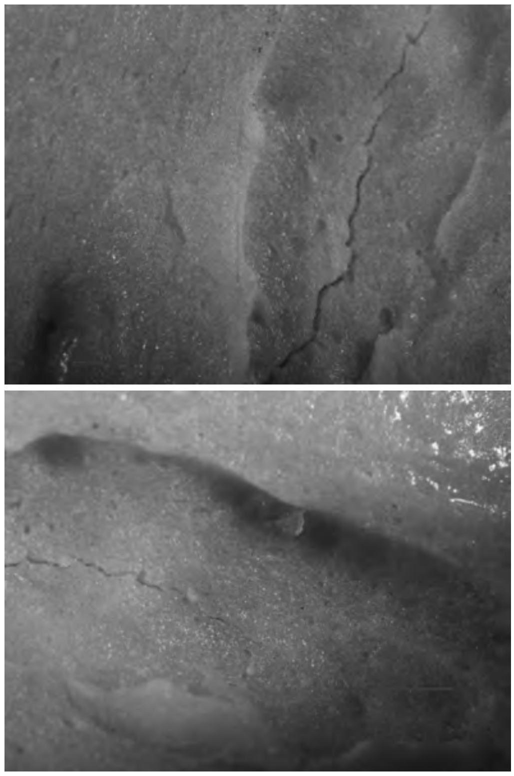

Fig. 1. Microcracks observed in PMMA directly after polymerization process

Rys. 1. Mikropęknięcia występujące w PMMA bezpośrednio po procesie polimeryzacji

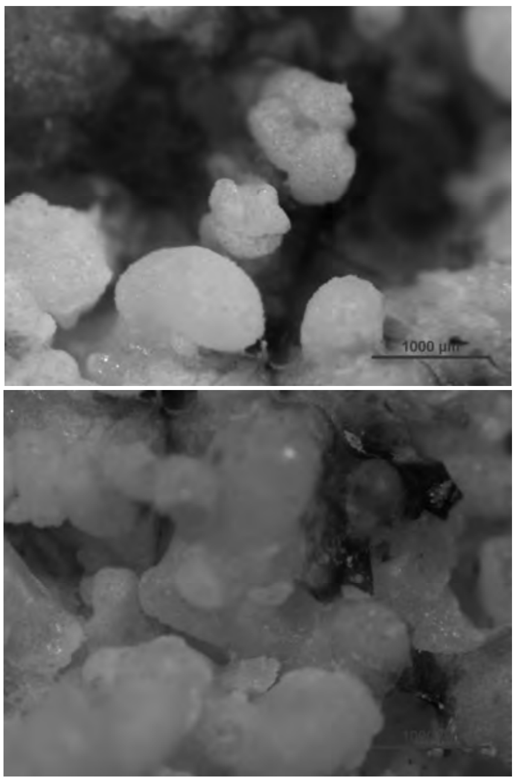

Fig. 2. PMMA - bone contact area

Rys. 2. Powierzchnia kontaktowa PMMA - kość

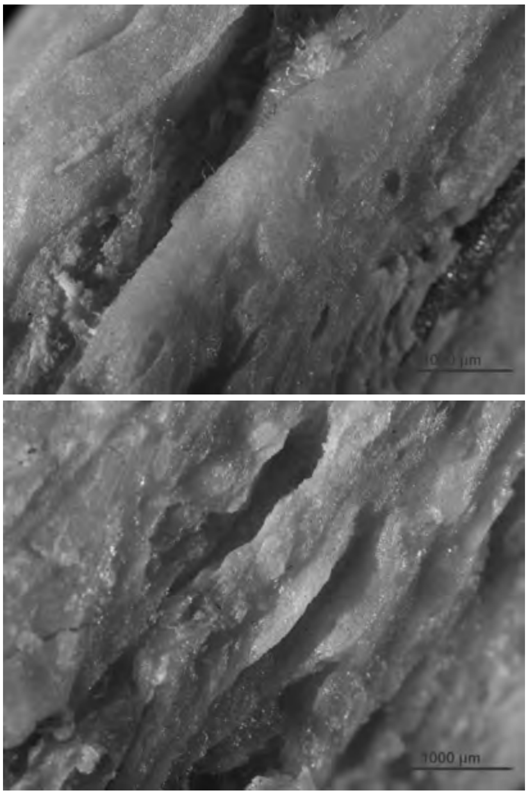

Fig. 3. Cracking of cement mass
Rys. 3. Pęknięcia masy cementowej

Fragments of cement mass chip and weaken the connection of the cement with the bone. Single fragments of PMMA unconnected with cement mass usually remain in place. A dangerous situation is when a fragment of bone cement chips in the area of proximal metaphysis or in the end area of the connection of the acetabulum and pelvis. Loose fragments of cement mass might get through to the articular capsule, and, in the case of lack of a capsule, they show tendencies to migrate to the body, which might have a very adverse effect on human health and may even threaten the life of a patient.

The crack resistance of cement mass with 5% filler shows considerable changes. The most beneficial changes, both in terms of strength and structure were reported for cement mass with carbon fibres. This type of composite is characterized by a reduction in areas with visible cracks, and separated fragments do not have the possibility to move easily since they are connected to the primary mass by carbon fibres (see Fig. 4).

Therefore, the determination of bone cement crack resistance and its modification aimed at increasing its strength is an essential problem. Bone cement Simplex P, popular in orthopaedics, was selected for the investigations of crack resistance. For the purposes of comparisons, crack resistance was also tested for bone cements with 5% fillers of:

1. bone-replacing BiO-OSS with granulation of 0.25÷÷1 mm
2. bone-replacing Poresorb with granulation of 0.16÷÷0.3 mm
3. ceramic material Al2O3, with granulation of 10÷20 μm
4. powdered animal bone with granulation of 10÷30 μm
5. carbon fibre

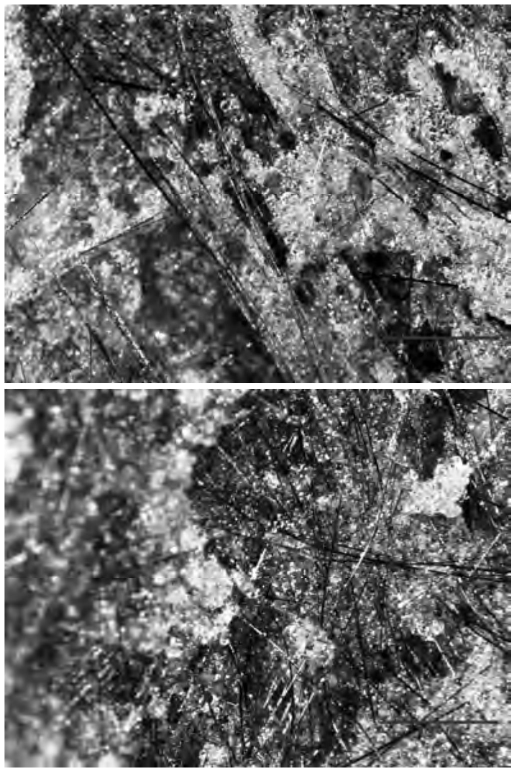

Fig. 4. PMMA/carbon composite fibre surface
Rys. 4. Powierzchnia kompozytu PMMA/włókno węglowe

The critical level of the stress intensity factor K_Q was adopted as a measure of crack resistance. The samples for the three-point bending of an SENB type were prepared for crack resistance tests. The dimensions of the SENB samples meet the plastic strain condition. It is assumed that this condition occurs when the following inequality holds true [7-10]:

$$B, a, \frac{W}{2} \geq 2.5 \cdot \left(\frac{K_{Ic}}{\sigma_y} \right)^2$$

where: B - sample width; a - notch length; W - sample height; K_{Ic} - stress intensity factor; σ_{Re} - yield point.

The stress intensity factor K_Q level was calculated based on the equation [7-10]:

$$K_Q = \frac{4 \cdot P_Q \cdot Y}{B \cdot \sqrt{W}}$$

where: P_Q - critical force N; Y - susceptibility function; B - sample thickness m; W - sample height m.

The susceptibility function Y from the numerator can be calculated based on the ratio of dimensions i.e. notch length to sample height (a/W). For a SENB sample [7-10]:

$$Y=\frac{6\cdot\left(\frac{a}{W}\right)^{\frac{1}{2}}\left\{1.99-\frac{a}{W}\cdot\left[1-\left(\frac{a}{W}\right)\right]\cdot\left[2.15-3.93\cdot\left(\frac{a}{W}\right)+2.7\cdot\left(\frac{a}{W}\right)^{2}\right]\right\}}{\left[1+2\cdot\left(\frac{a}{W}\right)\right]\cdot\left[1-\left(\frac{a}{W}\right)\right]^{\frac{3}{2}}}$$

Determination of the load P_Q critical level consists in drawing a secant in the obtained diagram for force as a function of displacement, which is sloped by 5% in relation to the previously determined tangent line. The location of the intersection of the secant with the chart determines force P_Q. After each measurement, the value of permissible non-linearity of the chart and the product of force P_Q in relation to maximal force Pmax was verified so that the latter did not exceed the critical level by more than 10% [7-10].

The investigations of crack resistance were carried out by means of an Inspekt Desk 20 machine manufactured by Hegewald & Peschke, equipped with a device for three-point bending. The K_Q level was calculated based on ten measurements of the P_Q force in all the types of cements included in the study. The critical levels of the stress intensity factor for different types of cement are presented in Table 1.

TABLE 1. **Critical levels of stress intensity factor for different types of cement**
TABELA 1. **Krytyczna wartość współczynnika intensywności naprężeń dla różnych rodzajów cementu**

Material name	Stress Intensity Factor [MPa·√m]
Clean SIMPLEX P	1.71
SIMPLEX P + Carbon filament	1.77
SIMPLEX P + BioOSS	1.65
SIMPLEX P + Poresorb	1.62
SIMPLEX P + Osseous crumbs	1.42

In order to compare the results, numerical calculations of the stress intensity factor (WIN) were also carried out for the three-point bending of a SENB sample made of SIMPLEX P + carbon fibre. The numerical tool used in the FEM calculations was ABAQUS/ Standard software which features modern calculation procedures in this area. The numerical calculations were carried out in consideration of the empirical data which determined the conditions initiating the process of cracking in polymer cements. The results of the numerical calculations were verified with the results from the empirical investigations. Numerical analysis based on the finite elements method (FEM) was carried out for the spatial model of a sample for crack resistance testing of the SENB type made of polymer cements. The SENB sample was subjected to three-point bending. In order to build a numerical model, a structural grid of finite elements of a hexagonal type was employed. Discretization of the SENB sample was based on twenty-node solid elements of the C3D20R type with a shape function of the second order, with 3 translational degrees of freedom in each node. The support elements and pressing rod were represented by rigid elements of the R3D4 type. Figure 5 presents a general view of the calculation model of a sample for crack resistance testing of the SENB type. The boundary conditions for the numerical model were defined through the fixation of lower supports, whereas the load was modelled through moving the rod vertically, according to the direction of the displacement vector. The contact interactions of surface-to-surface contact were defined between the supports and the rod and the SENB type sample. The numerical model required taking into consideration the singularity of the FEM grid near the peak of the crack (pre-crack fatigue). It is recommended to divide the area next to the crack into smaller parts. This was achieved through division, ensuring a grid in the shape of concentric 'circles' in relation to the crack peak. In the first 'circle', fifteen-node solid elements of a wedge type (C3D15) with a shape function of the second order were used, where the nodes from the centres of the side edges of the element were 'dragged' to 0.29 the length of the edge (when calculating from the peak of the fatigue pre-crack), thus ensuring FEM grid singularity in the crack peak. An example of the division into finite elements in the consideration of 8 circles is presented in Figure 6.

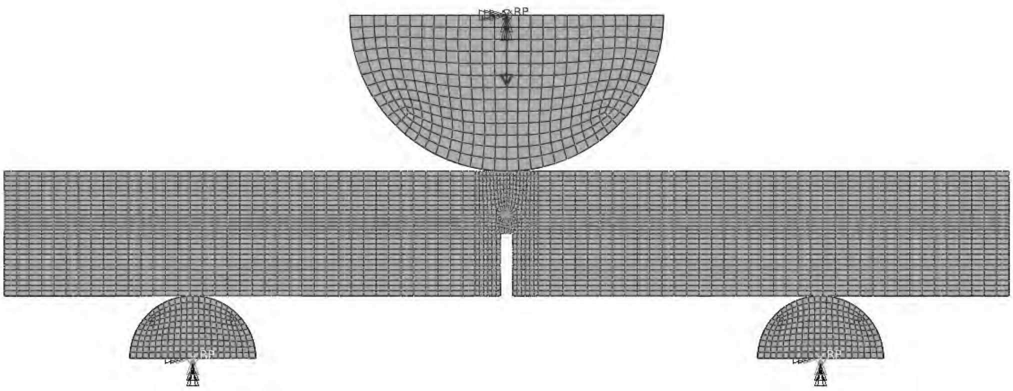

Fig. 5. General view of calculation model for SENB type sample for crack resistance testing
Rys. 5. Widok modelu obliczeniowego próbki do badań odporności na pękanie SENB

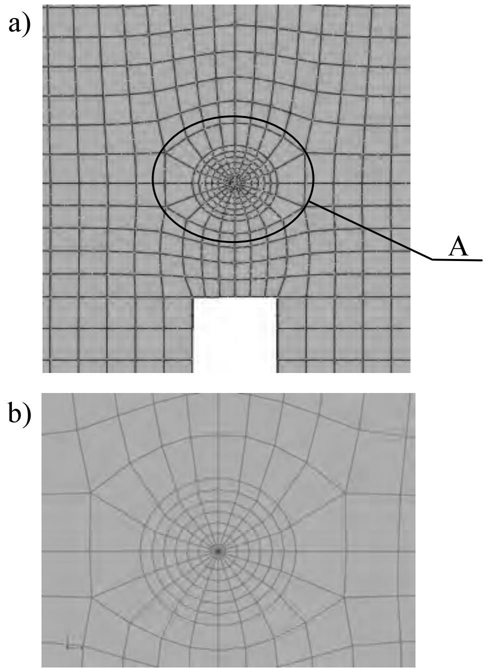

Fig. 6. Grid of finite elements near crack peak: a) general view, b) detail A

Rys. 6. Siatka elementów skończonych w pobliżu wierzchołka rysy: a) widok ogólny, b) widok szczegółu A

In order to describe the properties of polymer cement, the model of a linear elastic body was used. This model assumed that the value of the strain is directly proportional to the value of stress, until the moment of total breaking of the SENB sample. It was also assumed that the polymer cement of SIMPLEX P + carbon fibre is a quasi-isotropic body. For this definition of material, it is necessary to define Young's modulus E and Poisson's ratio ν ($E = 2400$ MPa, $\nu = 0{,}3$).

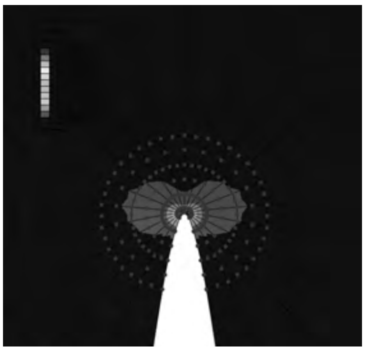

Fig. 7. Distribution of stress according to H-M-H hypothesis in fourth circle at moment of crack initiation

Rys. 7. Rozkład naprężeń według hipotezy H-M-H na czwartym okręgu w chwili inicjacji pęknięcia

The values of the stress intensity factor were read for each of the eight circles. Based on the author's own experience and literature data [5, 6], the stress intensity factor K_I level is neglected for the first three circles in order to avoid the undesired effect of singularity near the crack peak. This caused the results for the circles from 4 to 8 to be adopted for calculations of the stress intensity factor K_I level. The stress distribution according to the H-M-H hypothesis in the fourth circle at the moment of crack initiation is presented in Figure 7. The stress intensity factor level calculated numerically for the cement with carbon fibre was 1.91. The conformity of the numerical calculation with the empirical calculations was found for the model of a linear elastic body at the level of 92%.

CONCLUSIONS

The numerical modelling techniques used in the work for analysing the phenomena of the cracking process of SENB samples from PP and PA6 composites assure convergence of the calculation results with the results obtained from the experiments. It confirms the adequacy of the FEM discrete models that were formulated and it is the ground for further research in this field, with the use of numerical methods as an alternative investigation method that could be the completion and an extension of crack resistance research. It is forecast that in the next phase of numerical simulations, some theoretical considerations of the cracking process will be made using other body models that can be representative for composites with thermoplastic polymer matrices. Numerical calculations allow for the determination of the stress intensity factor K_I level by means of the finite elements method. The results of the numerical calculations confirmed the conformity of the stress intensity factor levels with the results obtained from the empirical investigations. The model of a linear elastic body assumes that crack propagation occurs at a very low plastic strain in the crack peak area. The model of the cement reinforced with carbon fibre employed in the study is entirely sufficient to obtain satisfactory numerical calculation results.

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