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THE ROLE OF EXPERIMENT IN THE PROBLEM OF RELIABILITY COMPUTATION OF THE CERAMIC HEAD OF THE HIP JOINT ENDOPROTHESIS

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This paper is concerned with the role of experiment in the problem of reliability computation of the ceramic head of the total hip joint endoprothesis. The reliability is determined by the stochastic approach which is based on Weibull's weakest-link theory. The stress in the ceramic head and the material parameters of the ceramics used are the input data of the analysis. The experiment in the stress computational modelling serves as verification of the results and a source of the input data. The ceramics material parameters are gained from the statistic analysis of the bending test results.

1. Problem formulation

The total hip joint endoprotheses belongs among most frequently applied replacements. The hip joint endoprotheses underwent construction, shape, technology and material developments of its own. The heat treated steel, polyethylene, ceramics and again steel with special surface treating were gradually used for the heads and the cups. The endoprothesis heads made of ceramic materials on aluminium or zirconium basis are widely used in this time. The ceramic materials used for the replacements are used for their desirable qualities such as high hardness, wear resistance and high biocompatibility. Among its negative qualities are the low value of the fracture toughness and the accompanying high predisposition for the brittle fracture. This fracture type has recently occurred in connection with a number, by no means negligible, of already applied total endoprotheses. This is the reason, why determination of their reliability becomes a actual problem.

This paper deals with one element of this system - the ceramic head. The problem, which is being solved at the Department of Solid Mechanics, is on the general level formulated thus: the task is to evaluate the reliability as regards the fracture limit state of the total endoprothesis ceramic head. Ideally, this problem should be solved for the "operation conditions" in the human body which, however, the recent level of our knowledge and technical possibilities do not allow. This problem is therefore solved in accordance with foreign approaches (for example that specified by the French norm for the determination of the static strength of the hip joint ceramic head [1]) under force conditions which are different from physiological ones.

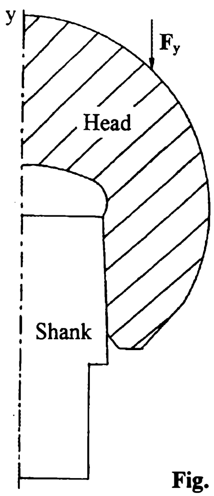

Fig. 1

2. Methodology of the problem solving

The determination of reliability determination as regards the fracture consists of two main phases. The first phase consists in the determination of the stress and deformation; the second is the determination of reliability proper. The way of the stress determination depends on the body geometry, the loading manner, relationship to the environment and the material properties. The total endoprothesis is a biomechanical system which consists of shank, head and cup. The structure of the modelling endoprothesis (without cup) in testing conditions is shown in Fig. 1. It is evident that for the head stress determination one cannot use the analytical method. Therefore the program system of finite element method - ANSYS 5.3 was used. The input data of the computational modelling are the following:

- geometry of the model system Fig. 1,
- system loading - concentric line load with resultant force which is identical with the axis of the system symmetry (axis y),
- constrains,
- contact condition between the head and the shank - data concerning the coefficient of friction and the quality of the contact areas:
    - surface quality of the shank cone areas:
        - smooth shank cone (system with smooth shank cone will be designated S_s from now on),
        - shank with teeth (system will be designated S_t),
    - production inaccuracies of the contact areas of the head and the shank:
        - deflections from the system's nominal value of degree of taper,
        - non-roundness of the contact areas,
- material parameters of the system elements.

The axis symmetry was utilized for the solution of the problem of stress for the ideal system produced without production inaccuracies (designated VAR.0) and for the system with the production inaccuracy type "deflections from nominal degree of taper" (designated VAR.α, where α is the inaccuracy value - Fig. 2). The nominal value of the degree of taper is 5°43'30". The maximum value of the difference between the shank cone vertex angle and that of the head is, according to the drawing. The system symmetry was utilized for the case of the inaccuracy type "non-roundness" (the maximum value of this inaccuracy is 16μm according to

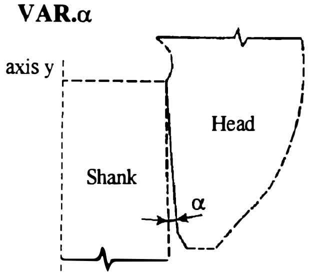

Fig. 2

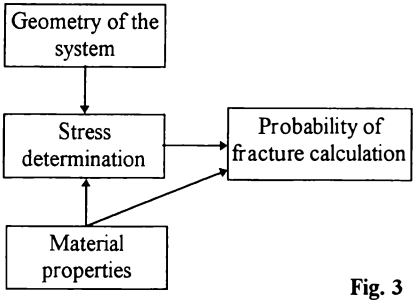

Fig. 3

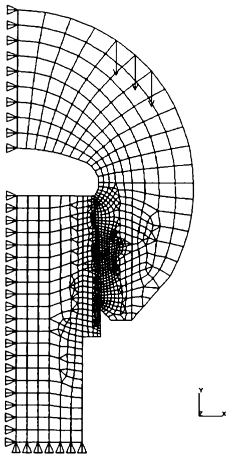

Fig. 4

the drawing). The meshing of the axis symmetry system, boundary condition and load are shown in Fig. 4.

Recently, the stochastic approach has been used for the determination of the ceramic components reliability and in this way the component fracture probability has been calculated. This approach is based on Weibull's weakest-link theory. The input data of the computational model are stress in the component and material parameters in connection with the fracture process. The scheme of the input of the reliability determination algorithm is shown in Fig. 3.

3. The role of experiment in computational modelling

The computational modelling has a dominant place in the solution of technical and non-technical problems. However, this does not mean, that experiments and experimental modelling lose on its significance. The experimental modelling is independent instrument for the solution of problems there is no convenient mathematical theory or theory exists but it is mathematically unsolvable or there is no computational instrument for the computational realization or input data are not available. Of course the experiment plays an irreplaceable part in the process of computational modelling which applies to these functions:

- the source of information for building the system of essential input values for problem solving,
- the source of information for theory building,
- verification of the theory accuracy gained in some other way,
- input data source,
- verification of the computational modelling results.

3.1. The role of experiment in the computational modelling of the head reliability

The experiments and technical measurements in computational modelling of the head stress were exerted in these phases:

- *the teeth shapes and sizes were measured.* The profile-measurement machine ME-10 was used for this purpose. The model tooth shape was found from the profile record of the shank cone surface. This shape was a triangle with the teeth height h=0,06mm and the teeth pitch p=0,2mm [3]. The teeth measurement was realized also after the experiments (after the destruction of the head). From the comparison of the teeth profile records before and after the experiments it follows that the shape changed from a triangular to the trapezoid. The teeth height decreased with the new height being h'=0,04mm. From the analysis of the shank material characteristics it follows the impossibility of the teeth plastification (viz. further on). This shape variation was caused by wearing of of the test shank teeth. This conclusion was confirmed by the analysis of the head contact cone after its destruction, on which the remains of the abrasive wear were found.

- *shank and head material parameters was researched.* The specimens were produced from the test steel shanks after the experiments. These specimens were tested on the tensile testing machine. The σ-ε graph implies, that the material behaviour of the shank is almost linear with the following parameters: $R_{p0,2} = 800$ MPa, $R_m = 890$ MPa, ductility A = 6,2%, reduction of area Z = 30%. Therefore, the shank material for the computational modelling is considered to be linear and isotropic with parameters: $E_s = 2,1.10^5$ MPa, $\mu_s = 0,3$.

The deflection influence on the load is possible to gain from the bending test of the ceramic specimens (ČSN EN 841-1). From these values and from the geometry measurements is possible to calculate the value of the Young's modulus $E_h = 3,9.10^5$ MPa. The value of μ_h is determined from the material norm and it is equal to $\mu_h = 0,23$.

- *from the comparison of the experimental results and the result of the computational modelling one arrives at a credible value of the coefficient of friction between the head and the shank.* Fig. 5 shows the dependencies of the head-shank insertion on loading. The experimental values are represented by the solid lines for S_s and S_t. The values from the computational modelling are represented by the thin lines for VAR.0 (without production inaccuracies) for different values of the coefficients of friction between the head and the shank. The main difference in shape of the experimental and computational curves is for low loading (to the 10kN for S_s and to 17kN for S_t). The experimental curves are non-linear in this interval; more precisely, the bigger the load, the lower the value head-shank insertion - as if the coefficient of friction increased with the load increase. This non-linear dependence is the cause of the production inaccuracies of the contact areas of both the shank and the head. The contact is realized only in some regions of the contact area when the loading is started owing to the production inaccuracies. The inaccurately produced contact areas are deformed by high pressure in the latter regions. The resistance of the insertion increases with the increasing load. The mechanism of this process is very complicated and its analysis is impossible

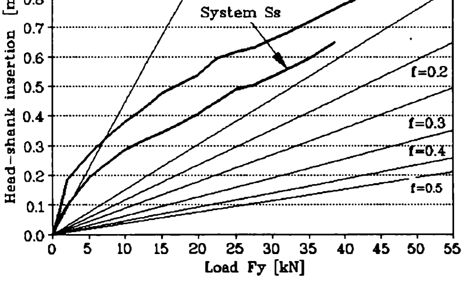

Fig. 5

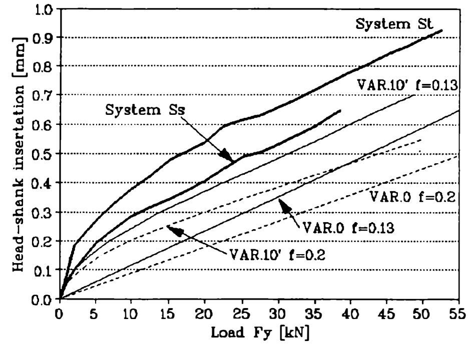

Fig. 6

in this paper. The production inaccuracies are eliminated at a definite load (in our case 10kN for S_s and 17kN for S_t) and the contact is more or less realized at the whole contact area. The insertion resistance is constant from this load on and it presents itself by the linear dependence of load and the head-shank insertion (this partial conclusion is confirmed by the computational modelling - viz. further on). From the analyses of the slopes of the experimental and computational curves it follows that the slope of the computational curve with coefficient of friction f=0,13 is almost the same as the slope of the experimental curves for high load. The coefficient of friction, which is the input data of the computational modelling, is possible to specify in this way. Fig. 6 shows the dependencies of the load on the head-shank insertion for experimentally gained values (solid lines) and for values gained from the computational modelling (thin lines) for the coefficients of friction f=0,13 and f=0,2 and for VAR.0 and VAR.10'. The experimental dependencies and VAR.10' dependencies are similar in shape. The non-linear dependencies gained from computational modelling are found when the loading starts; for higher load the dependencies are almost linear. The transition between the non–linear and linear dependency corresponds to the situation when the production inaccuracies of the contact areas are removed by the deformation of the system (the contact is realized at the whole contact area now). Better harmony between experimental and computational results will be reached for lower coefficient of friction, namely for f=0,13.

The ceramics material parameters for the fracture process were determinated from the experimental results gained from a bending test performed on a set of specimens. For the process of determination viz. [2]. σ_u, σ_o and *m*. are the ceramic material parameters. The value of σ_u presents the stress below which fracture will not occur; σ_o presents the normalized material strength of the volume unit; *m* is Weibull modulus which is connected with the dispersion variance of the values measured.

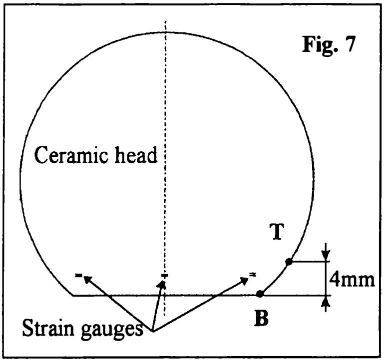

Fig. 7

The experiment proved useful in the final phase of the computational modelling; namely, in the verification of its credibility. The dominant stress and strain are in the circumferential direction, as it follows from the computational modelling. Therefore six electric resistance strain gauges (Hottinger 0,6/120LY11) were stuck to the head in the circumferential direction. Two strain rosettes (Micro-measurements WA-06-030WR-120) with the basis 0,72mm were orientated so that one gauge was orientated in the circumferential direction Fig. 7. Fig. 8 and 9 show circumferential strain values gained from the experiments (solid lines) and those gained from the computational modelling (thin lines). Each figure shows specific areas which are determined by the extreme strain gauge values (for the experimental values) and the areas for computational values are determined by the strain values in the point B and in the

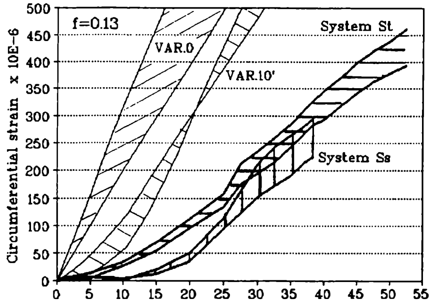

Fig. 8

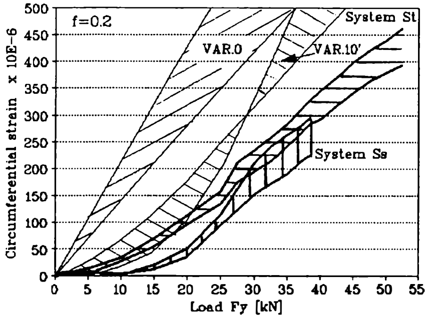

Fig. 9

point T (Fig. 7). From the analysis it follows that the harmony between experimentally measured strains and strains from computational modelling would be reached if the coefficient of friction f=0,2 is used (Fig. 9), because the strain values of VAR.10' approximate the experimentally gained values more than strain values for f=0,13 (Fig. 8).

A discrepancy occurs now, because on the one hand the analysis of the diagram load - head-shank insertion implies the coefficient of friction f=0,13 (the experimental and computational dependencies have the same slope (Fig. 6)) and, on the other hand, based on the strain comparison it would be more suitable to choose the value of the coefficient of friction higher than f=0,13. Hence, it is possible to define a interval in which the actual value of the coefficient of friction is found f∈(0,13;0,2). New results of computational modelling which consider non-roundness and the combination of both inaccuracies (non-roundness and degree of taper deflection) will contribute to the narrowing down of the latter frictional interval.

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