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Fatigue Testing and Calculation of a Conical Pedicle Screws for Spine Fusion

Š. Major [1,2,*], V. Kocour [1], Š. Hubálovský [3]

[1] *Institute of Theoretical and Applied Mechanics, Academy of Science, Prosecká 809/76, 190 00 Praha 9, Czech Republic*

[2] *Department of Biophysics, Faculty of Medicine, Charles University of Prague, Šimkova 870/13, 500 38 Hradec Králové, Czech Republic*

[3] *Department of Informatics, Faculty of Science, University Hradec Králové, Rokitanského 62, 500 03 Hradec Králové, Czech Republic*

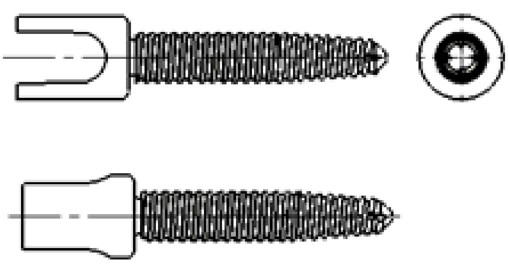
* *s.major@seznam.cz*

Abstract: The main goal of spinal surgery is to stop the pain caused by joints that have worn out over time or degenerated due to disease. Spinal fusion joins together the vertebrae on either side of a joint in spine. Fixation with pedicle screws is one method which is used by surgeons for fusing the vertebrae in spine. Implants are subjected to many loading cycles during their life. Any damage to the implant leads to significant complications in the treatment and causes considerable pain. For this reason, it is necessary to pay close attention to testing and fatigue prediction of implants.

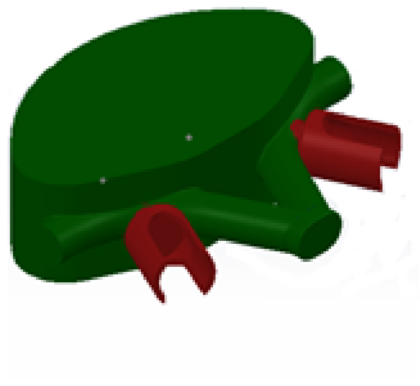
Keywords: Spinal-Implant; Pedicle-Screw; Fatigue Life; Notched Specimen; Titanium Alloy.

1 Introduction

Implants for spinal fusion are consisting of screws penetrating into the vertebrae (pedicle-screw) and the other elements, such rods and plates [1, 2]. During their lives, implants are subjected to many loading cycles. This loading can lead to a breach of the implant. Failure of the implants causes not only pain for the patient, but may cause further injury of spine or other internal organs. For this reason, it is important to pay attention to testing and fatigue life prediction of implants.



(a) geometry of pedicle-screw with conical thread



(b) pedicle screw placement in vertebrae

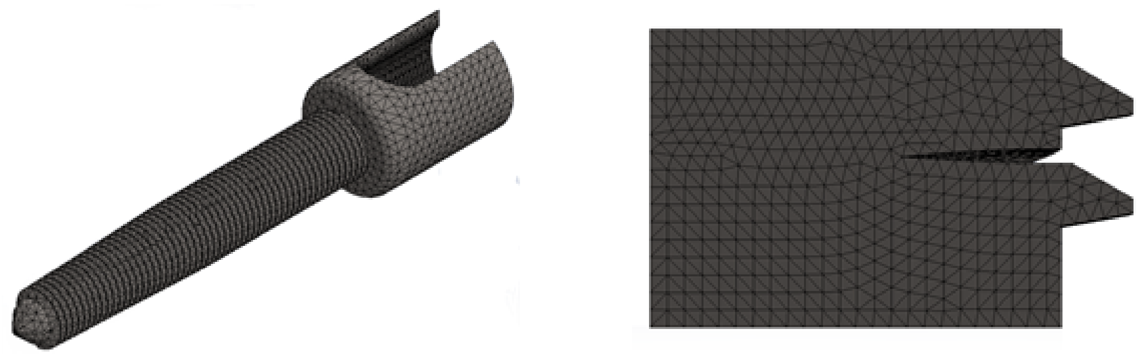
Fig. 1: Conical pedicle screw for spinal-surgery.

2 Material and Geometry of Implant

Implants used in this study were made of titanium alloy 6AL4 V ELI, also known as Grade 23, without any surface treatment. Mechanical properties of this alloy are: E = 104.5 GPa, σ_u = 860 MPa, and σ_y = 820 MPa. For calculation of fatigue life, it is necessary to know constants of Paris-Erdogan law: $C = 5.1 \times 10^{-12}$ and n = 4.2 for the crack growth in mm/cycle, stress intensity factor K in MPa.m$^{0.5}$. Geometry of conical pedicle-screw is shown in Fig. 1. This figure also shows the imposition of a pair of screws in the implant.

3 Theoretical Prediction

Theoretical calculation of fatigue life of pedicle-screw is based on method proposed by Navarro [3] and for comparison other criteria of fatigue life prediction [4] were applied on this problem. The advantage of this new model is in combination of initiation and propagation phases without requirement to define boundary length of crack to differentiate between the two phases of crack growth. 3D-model of implant and vertebrae was prepared and solved in ANSYS for calculations. Finite element model of contact between vertebrae and thread was characterized by null displacement. Another model finite element model was separately created for calculation of stress-intensity factor along the path of crack.



(a) conical pedicle-screw

(b) the rack on the bottom of the threat

Fig. 2: Finite element models of screw and the local of the crack.

This model assumed semi-elliptical crack on the bottom of the thread. Dimensions of the crack are characterized by length of semi-axis a and b, perpendicular and tangential to the threat. When propagation of crack is studied, it is necessary determine the stress intensity at the forehead of crack. Stress intensity factor in the thread is calculated using J-integral. The propagation of calculate the number of cycles N_i needed to reach the length of crack a (corresponds to semi-axis a):

$$N_i(FS, a) = N_{Total}(FS) - \int_{a0}^{a} \frac{da}{C\Delta K^n} \tag{1}$$

where N_{Total} is the total number of cycles to failure, C and n are constants from Paris-Erdogan law, ΔK is increment of stress intensity factor and FS is damage parameter proposed by authors Fatemi and Socie. The FS damage parameter is expressed as a function of the maximum shear strain amplitude $\Delta\gamma_{max}$/2, and the maximum normal stress acting on the maximum shear strain plane over the cycle, $\sigma_{n,max}$, as:

$$FS = \frac{\Delta\gamma_{max}}{2}\left(1 + k\frac{\sigma_{n\,max}}{\sigma_y}\right) \tag{2}$$

where σ_y is the material monotonic yield strength, and k is a material constant which can be found by fitting uniaxial fatigue data to torsion fatigue data. The second phase of the fatigue process, propagation of crack through screw, can be described by equation:

$$\frac{da}{dN} = C\left(\Delta K^n - \left(\Delta K_{th}\left(\frac{a^w}{a^w - a_0^w - l_0^w}\right)^{\frac{1}{2}w}\right)^n\right) \tag{3}$$

where ΔK_{th} is the growth threshold for long cracks, exponential parameter w = 2.5), l_0 is the average distance to the first microstructural barrier and a_0 is so-called El Haddad parameter [5]. This parameter is defined by the relationship:

$$a_0 = \frac{1}{\pi}\left(\frac{K_{th,Long}}{\Delta\sigma_{FL}}\right)^2 \tag{4}$$

where $\Delta\sigma_{FL}$ is the fatigue limit of the material. When curves defined by Eq. 1 and Eq. 3 are merged, final curve described entire fatigue life of screw. From this picture is clearly visible, that the initiation phase represents only 6 % of entire fatigue life of pedicle screw. Various multiaxial criteria modified for fatigue life prediction of notched cylindrical specimen are described in the work [4], which corresponds to the case of the thread.

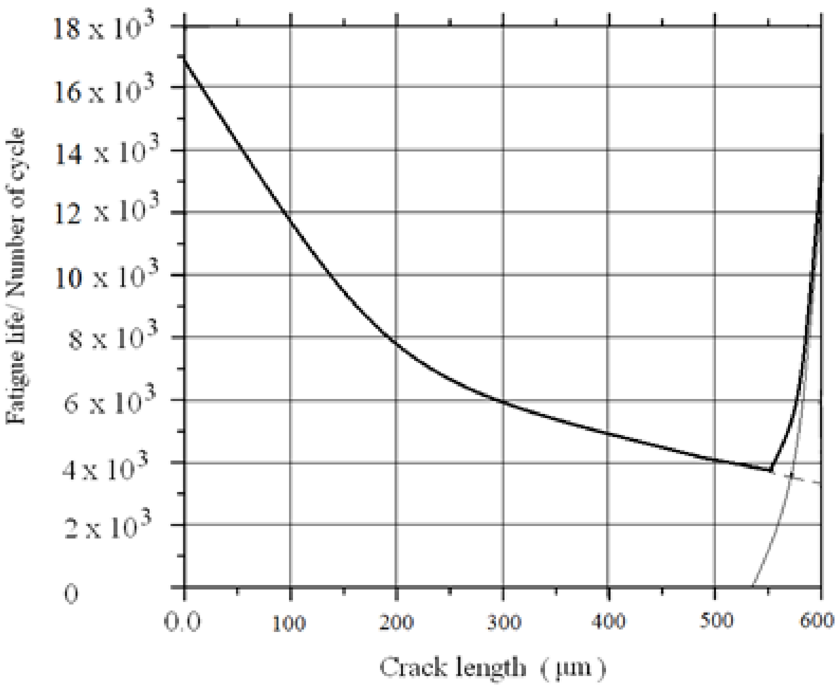


Fig. 3: Application of the prediction model for loading force F = 400 N. Final fatigue life of pedicle screw is marked by thick line, propagation stage is drawn by dashed line and thick line represents initiation phase. This shows that the initiation phase of fatigue life is only 6 % of total fatigue life.

4 Testing

The sinusoidal bending loading eccentrically was applied on the implant. Eccentricity of loading causes that the individual screws are subjected to a combination of torsion and bending. The loading frequency was 30 Hz. The implants were clamped in the artificial vertebra during test so that the device simulates the bone-metal contact. During experiments the samples were loaded by this forces F = 200, 300, 400, 500 N The experiment was conducted until failure of one of the screws. Results of experimental loading of pedicle-screw are shown at Fig. 4.

5 Conclusion

The method proposed by Navarro gives very good results. The method was the greatest success in the fatigue life prediction of pedicle-screw fatigue life under loading. The method allows description of fatigue process in the case of relatively small objects, due to the fact model cracks. Another reason for its success is, that the finite element model reflected screw fixation in the bone well. If we perform a comparison of theoretical

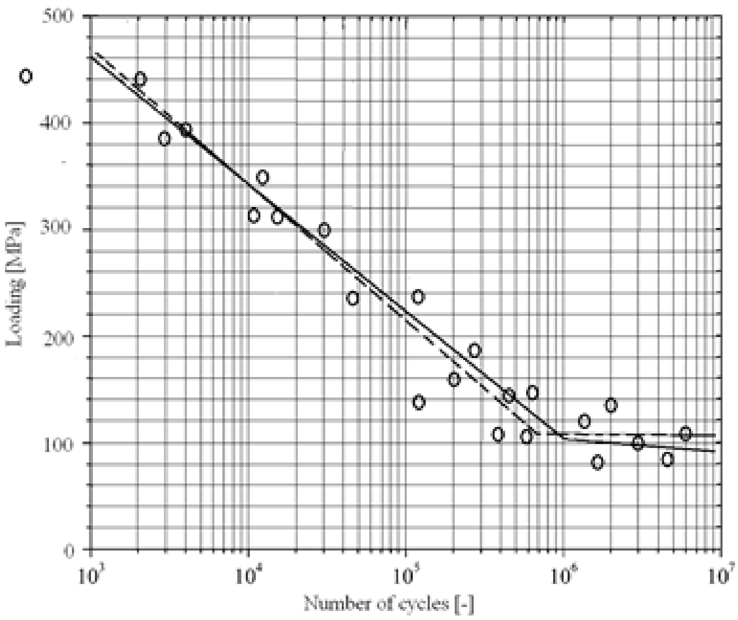


Fig. 4: Fatigue tests of implants and theoretical prediction of fatigue life of pedicle screws. Experimental points of pedicle screw failure are marked by circles. Theoretical prediction of fatigue is marked by solid line and experimental fatigue curve is represented by dash line.

lifespan forecast of the screw based on Navarro method [3], with other methods [4] (Goncalves method is best of them), it can be said that Navarro method gives 40 % better result than Goncalves method.

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References

[1] K. H. Bridwell, R. L. DeWald, The Textbook of spinal Surgery, Wolters Kluwer/Lippincott/ Williams & Wilkins, Philadelphia, USA.

[2] Ch. Chen-Sheng et al., Failure analysis of broken pedicle screws on spinal instrumentation, Medical Engineering & Physics 27 (2005), pp. 487–496.

[3] C. Navarro, J. Vázquez, J. Domínguez, A general model to estimate life in notches and fretting fatigue. Enginnering Fracture Mechanics (2011), pp.1590–601.

[4] Š. Major et al: “Effectiveness of the Modified Fatigue Criteria for Biaxial Loading of Notched Specimen in High-Cycle Region”, Applied Mechanics and Materials, Vol 732, pp. 63-70, Feb. 2015.

[5] M. H. El Haddad et al., Prediction of non-propagating cracks, Engineering Fracture Mechanics 1979;1; 11:573–84.