

INFLUENCE OF HYDROGEN EMBRITTLEMENT ON FATIGUE LIFE OF TITANIUM ENDOPROSTHESIS

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Abstract

Hip replacement is a surgical procedure in which parts of a hip joint are removed and replaced with a prosthesis, most commonly made of titanium-based alloys. Although considerable advances have been made in this field, the fracture is still one of the main problems associated with hip implant failure. This paper deals with the analysis of the premature failure of hip joint replacement. A 61-year-old patient underwent a left hip replacement in 2008, and revision surgery was required after 10 years. Many possible causes of failure include incorrectly chosen material microstructure, heat treatment, fatigue cyclic loading, or hydrogen embrittlement. This paper focuses on saturating the endoprosthesis with hydrogen. By examining the amount of saturated hydrogen in the Ti6Al4V alloy, it is possible to predict the fatigue life of the endoprosthesis. Comparison the hydrogen content in a used implant and sample saturated by cathode method, we estimate the amount of hydrogen that will be diffused in regular use. The experiment aims to find out and eliminate risk factors and reduce the number of revision surgeries for prematurely failed hip joint replacement. In practice, this means ensuring a dignified life for patients after surgery.

Keywords: Endoprosthesis, hip joint, hydrogen embrittlement, Ti6Al4V

1. INTRODUCTION

Ti6Al4V alloy is very sensitive to previous thermomechanical processing. The fatigue limit of Ti6Al4V alloy often runs from the ratio of primary α to the transformed β phase, from the size of the primary β grains, as well as the size of the α grains and the morphology of the $\alpha + \beta$ phase. All parameters affect the properties of the alloy, especially fatigue life [1]. At low temperatures, the mechanical properties of this alloy are largely influenced by the α phase. In addition to the patterns and morphology α uses, the fatigue life of the Ti6Al4V alloy is affected by aging and the content of hydrogen and oxygen. Increasing the levels of oxygen and hydrogen in the Ti6Al4V alloy reduces the fracture toughness. It is used by increasing the planar slip, supported by the arrangement of Ti₃Al production, which causes easy nucleation of cracks at the grain and phase boundaries. This tendency also helps with a high aluminum content, and thus the composition of commercial alloys rarely exceeds 6% [2]. Hydrogen creates cleavage and cracking of the interface due to the formation of hydrides (TiH₂). Alloys with a high level of β can help dissolve more hydrogen, reducing the reduced fracture toughness caused by hydrogen. Increased hydrogen content can lead to some changes in its physical and mechanical properties. The high hydrogen content in the material causes its degradation. This is most often manifested by a change in plastic deformation, tensile strength, yield strength and decrease in resistance to brittle failure. The term hydrogen embrittlement is used to degrade the material affecting hydrogen. Hydrogen can transfer the material to various stages of production, as well as during use [3].

Types of hydrogen embrittlement depending on hydrogen sources, types of damage and with the location of hydrogen in the microstructure [2]. Hydrogen can penetrate titanium through various information. In principle, two types are distinguished, namely in gaseous and liquid media. Hydrogen can only be transferred to the material in the atomic state. The basic premise is the decomposition of a hydrogen molecule on the surface of the material. The penetration of hydrogen into the material is influenced by the composition of the liquid medium, the condition of the titanium surface, resp. the presence of impurities on the surface. Hydrogen diffusion in solid groups is the only possible way of mass transfer [4]. The driving force of diffusion is the gradient of the chemical potential. The diffusion of hydrogen, which is present in the material in the interstitial positions of the crystallographic lattice, is governed by the laws of interstitial diffusion and it is possible to apply Fick's laws to it [5]. The diffusion rate of hydrogen in metals affects the structure of the material. A higher diffusion factor is found in metals with a body-centred cubic grid than a face-centred cubic grid [6].

Other interstitial elements - carbon and nitrogen, have a low solubility in the solid in titanium and, when the level of solubility is exceeded, form fine particles of TiC and TiN. These particles drastically reduce the ductility as well as the fracture toughness of titanium alloys and must therefore be removed [7].

2. EXPERIMENTAL MATERIALS AND METHODS

The Beznoska Trio implant was made of Ti6Al4V alloy according to ISO 5832-3. The implant is characterized by a modular stem with the probability of various variants of neck inclination. Fatigue tests were performed on the specimens using a Vibrophores Amsler 150 HFP Zwick / Roellpulsator to empirically verify the fatigue properties of the material. The experimental material was also used for hydrogenation tests using the cathode method on the constructed equipment. The samples were supplied by the manufacturer in the form of bars with a length of 55 mm and a square cross-section and dimensions of 10 mm x 10 mm (**Figure 1**). The chemical composition of the broken endoprosthesis was examined using a SPECTROMAXx device. To observe the microstructure, specimens were made by standard methods of metallographic preparation of titanium alloys on a TegraPol-15 automatic device from Struers. After grinding and polishing, the samples were etched with 10% HF. After metallographic preparation of samples from the neck and stem of the endoprosthesis, the microstructure was evaluated on a NEOPHOT 32 light microscope and on a TESCAN VEGA LMU2 scanning electron microscope.

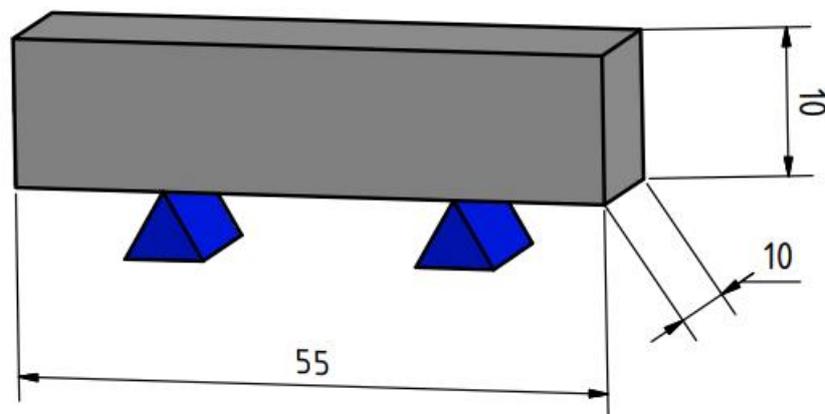


Figure 1 Dimensions of the experimental material [own study]

A sample with a size of 10x10x1 mm was taken from the failed neck of the endoprosthesis and subsequently analysed in a linear tandem ion accelerator 6 MV TANDETRON. The operating range of the accelerating voltage of Tandetron is from 300 kV to 6 MV.

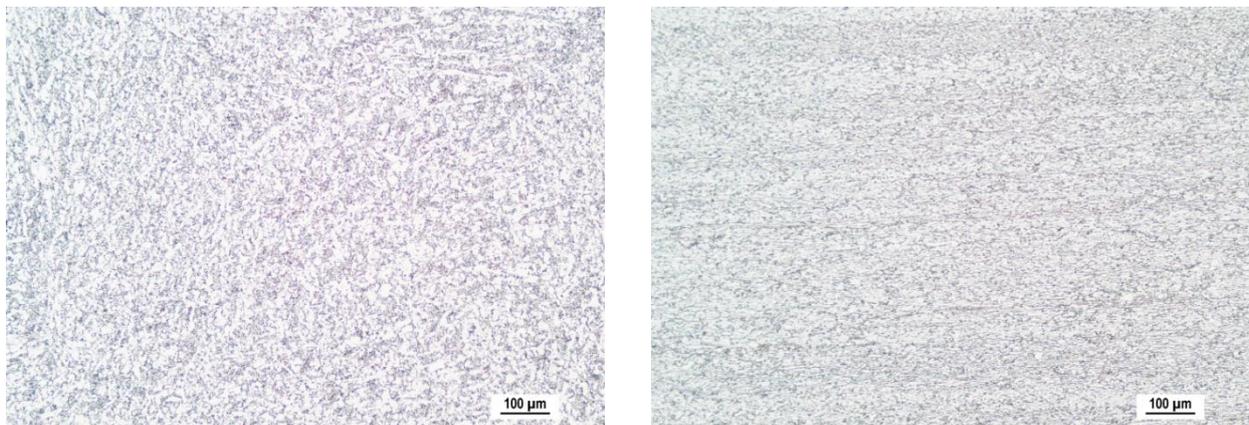
3. RESULTS AND ITS DISCUSSION

3.1. Microstructure

Titanium and its alloys are among the modern implant materials and are characterized by excellent corrosion resistance, good biocompatibility, reduced modulus of elasticity, and high strength. The company Beznoska uses the alloy Ti6Al4V for the uncemented Trio prosthesis. As well as the chemical composition, the mechanical strength of the metal material is also affected by its microstructure. The microstructure is a result of the thermomechanical processing of the material.

The microstructure (**Figure 2**) was formed by polyhedral grains of phases α with a hexagonal lattice and β with a body-centred cubic grid. There was a predominantly equiaxed α phase with a small amount of irregularly shaped β -phase at the grain boundaries of the α phase. The fine lamellae α had the same shape and size. This microstructure is in agreement with the heat-treated TiAl6V4 alloy at 1020 °C for 20 min. The morphology of the α phase may change with the increased cooling rate or alloying content. From the current knowledge, the dependence of fatigue life on the lamellar α -phase is known.

Despite the advantages of fine-grained titanium, its use is not straightforward. The fine-grained structure is not stable at temperatures higher than 600 °C. It requires modification of the current technology for the manufacture of titanium endoprostheses. Significant complications are also a considerable dependence of mechanical properties on the required bar diameter, limited production possibilities of suppliers, and a higher price [5].



a) cross-section, 10% HF

b) longitudinal section

Figure 2 Microstructure of specimen [own study]

3.2. Hydrogenation

Hydrogen embrittlement significantly contributes to shortening the life of the lumbar endoprosthesis. By comparing the amount of saturated hydrogen in the prematurely failed endoprosthesis with the starting Ti6Al4V alloy, it was possible to predict the amount of hydrogen that diffuses into the implant during use.

The hydrogen content (**Figure 3**) in the initial material is almost half as low as in the implant. The depth to which the hydrogen diffused is 0.08 μm , which can be considered negligible. Such an amount of hydrogen could also enter the sample from the atmosphere.

The amount of hydrogen in the failed neck of the endoprosthesis diffused during application in the patient's body. The accumulated hydrogen penetrated to a depth of 100 times compared to the initial material of the Ti6Al4V alloy. By demonstrating the presence of hydrogen in the failed neck of the hip endoprosthesis, it is possible to classify hydrogen embrittlement as one of the factors that significantly affect the life cycle and functionality of implanted endoprostheses.

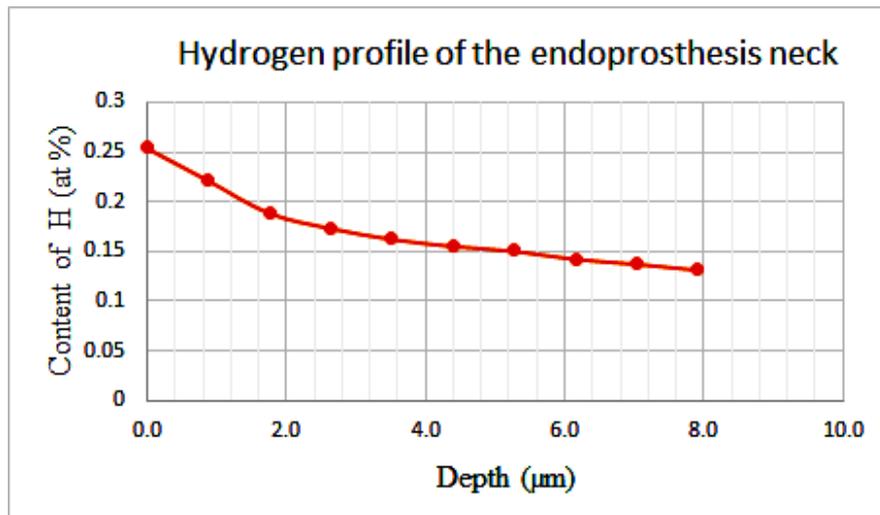


Figure 3 Hydrogen profile of the endoprosthesis neck [own study]

3.3. Fatigue tests

After hydrogenation, the experimental test bars were subjected to fatigue tests by three-point bending. Although the slope of the curves is very similar, based on the comparison of the curves, it can be argued that the hydrogenated samples have lower fatigue life values than the initial ones, because the fractures occurred during lower loading stress.

The S-N diagram (Figure 4) has a decreasing course in both cases. It is characterized by a decrease in voltage amplitude. At this voltage amplitude, all samples exceeded the specified number of cycles, some failed, and some reached 10^7 cycles without failure. Up to 10^7 cycles of 5 samples at baseline and one sample after hydrogenation were tested without fracture.

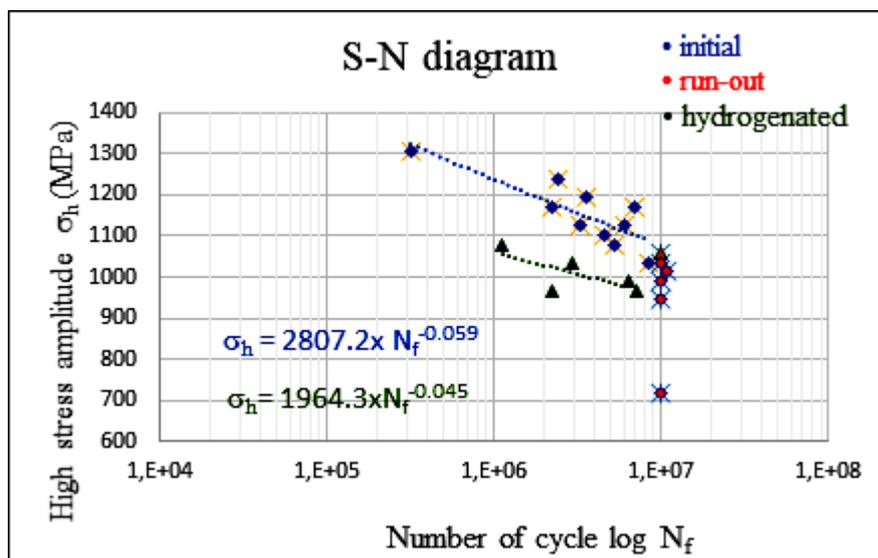


Figure 4 S-N diagram [own study]

4. CONCLUSION

- By demonstrating the presence of hydrogen in the failed neck of the lumbar endoprosthesis, it is possible to classify hydrogen embrittlement as one of the factors that significantly affect the life and functionality of implant endoprosthesis.

- The hydrogen content of the implant was almost half that of the starting material and the accumulated hydrogen penetrated to a depth of 100 times compared to the starting experimental material of the Ti6Al4V alloy.
- In fatigue tests by three-point bending with a specified number of cycles $N_f = 10^7$, it turned out that at a medium stress $\sigma_m = -720$ MPa, the fatigue life increases with decreasing stress amplitude. From the generated S-N fatigue life diagram, it is possible to determine the equation for the regression power curve for the amplitude of the upper stress: $\sigma_h = 4287 \cdot N_f^{0.153}$.

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REFERENCES

- [1] LYNCH, S. *Hydrogen embrittlement phenomena and mechanisms*. Melbourne: Woodhead Publishing, 2011.
- [2] STEINER, J.E. *Control of flaking and other hydrogen problems in heavy forgings*. 1982, Current Solutions to Hydrogen Problems in Steels.
- [3] SOJKA, J. *Resistance of steels to hydrogen embrittlement*. Ostrava: Technical University of Ostrava, Faculty of Metallurgy and Material Engineering, 2007.
- [4] RODRIGUES, D. In vivo severe corrosion and hydrogen embrittlement of retrieved modular body titanium alloy hip-implants. *Journal of Biomedical Materials Research*. Part B: Applied Biomaterials: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials, 2009, vol. 88, pp. 206-219.
- [5] CAMERON, H.U. The long-term success of modular proximal fixation stems in revision total hip arthroplasty. *The Journal of Arthroplasty*. 2002, vol. 17, pp. 138-141.
- [6] BARRACK, Robert L. Orthopaedic cross fire®—stem modularity is unnecessary in revision total hip arthroplasty: *The Journal of Arthroplasty*. 2003, vol. 18., pp. 98-100.
- [7] ASM. 1996. *Fatigue and Fracture*. USA: s.n., 1996.