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CASE STUDY AND FAILURE ANALYSIS OF A TOTAL HIP STEM FRACTURE

ABSTRACT

A total hip replacement is a procedure that requires removal of the affected joint lesions and replacing it with artificial elements. Nevertheless, like any invasive surgery, it is associated with the risk of complications, including joint infection, fracture of the bone during and after surgery, scarring and limitation of motion of the hip, and loosening of the prosthesis. In this work we present and describe the results of its investigations. In order to determine the mechanism of failure, a broken stem components were analyzed by means of macroscopic and microscopic observations and hardness measurements. The hardness, microstructure and chemical composition of the broken part of the hip stem were analyzed. Microscopic examination revealed numerous defects in material. Among them are pores and emptiness, located on the outskirts of the tested samples and a plurality of micro-cracking, debonding and delamination of the material due to the overloading of a fatigue character. There were no changes caused by intergranular corrosion or pitting, which may indicate for an even distribution of the major alloying components such as chromium and nickel. Observations of the material by using scanning electron microscopy (SEM), clearly proved that the destruction was caused by material fatigue. The investigation showed that the crack had originated due to a high stress concentration on the lateral corner section of the stem. Large surface of the fatigue crack zone area indicated for small stresses and small crack propagation velocities. There was a clear correlation between the grain size of the steel hardness. The results of hardness test revealed a significant increase hardness of stem in relation to the normative values. In addition, the measured average grain size is less than the standard accepted. Using Solid Works simulation and FEM a model of the stem was created and analyzed in terms of strength and rated the distribution of the generated stress. The finite-element analysis confirmed that there is the highest stress concentration in the middle of the stem

Keywords: hip replacement, isolated fracture, fatigue fracture

INTRODUCTION

Hip is one of the biggest working joints of the body. Any problem in this arrangement can seriously impact entire body and the ability to perform normal activities. When the joint is severely damaged due to arthritis or other problems, hip replacement surgery may be recommended [1]. This procedure can greatly improve quality of life by relieving pain associated with a hip problem, allowing more active life. Primary hip prosthetic has become one of the most successful operation techniques in orthopedic surgery, which is a popular strategy used for restoring the normal function of the hip joint damaged by fracture or disease [2]. Unfortunately, the hip prosthesis is not the ultimate solution to health problems. The daily activities of human body act as cyclic forces on the joint prosthesis leaving dynamic stresses on the prosthesis and the cement. During service life, surgical implants are exposed to an aggressive environment in terms of corrosion, wear and loading. This wide range of variables has resulted in a wide range of failure mechanisms [3]. Fracture of the femoral stem constitutes a dramatic long-term complication of total hip surgery. The incidence of this complication varies with many factors, including the device used, the material from which the prosthesis was made, the surgeon, and the patient population [4-5]. Relatively high rates of fracture of the femoral stem of total hip arthroplasties were seen with early designs manufactured in the 1960s and 1970s because of the material's low fatigue strength and the presence of metallurgical defects [6,7]. Stems generally failed via a fatigue mechanism because of unfavorable biomechanics such as various positioning, loosening, loss of proximal support, geometry of the stem, or surface damage of the implant [3]. Fractures have been reported in a variety of prosthetic designs and materials. The use of high-strength materials including forged cobalt chrome, titanium alloy and high-nitrogen stainless steel, as well as further development of stem design and stem geometry, have led to a reduction in the incidence of this complication, and the occurrence of fracture with modern femoral stems is now a very rare event [8-11]. The stem examined in this case study was manufactured from high nitrogen stainless steel (REX 734 grade, ASTM F 1586). Nitrogen added to austenitic steels can simultaneously improve fatigue life, strength, work hardening rate, wear and localized corrosion resistance (pitting, crevice and intergranular corrosion) [12]. Nitrogen prevents the formation of delta ferrite. To increase the solubility of nitrogen, the addition is made in conjunction with a reduction in nickel and an increase in manganese content [12-13]. It retards the formation of chromium-molybdenum brittle phase and substantially strengthens the steel via an interstitial hardening mechanism [14]. Nitrogen is also an austenite stabilizer, and thus, the nickel content can be reduced [12-14]. Because of this, the high nitrogen stainless steels are being considered as a new class of bioengineering materials.

MATERIALS AND METHODS

The stem was forged using high nitrogen stainless steel. The failure occurred after only 3 years service. A general view of fractured stem surface in the Fig.1 was presented. After revision, the two sections of the fractured stems were prepared for further analysis. A small piece was cut from the stainless steel sample and prepared metallographically by using a standard techniques, so that a microstructure could be observed in cross-section and evaluated. To compare the chemical composition of the fractured stem with ASTM F1586 standard spark emission spectroscopy (Thermo ARL Quantris, Switzerland) was used. Detailed microscopic examinations of the microstructure after etching polished samples were carried out by a Nikon Eclipse LV1000 optical microscope (OM). The fracture surfaces of the stems were examined by means of a Hitachi S-3000N Scanning Electron Microscopy (SEM) equipped with Energy Dispersive Spectroscopy (EDS) detector. Hardness measurements were performed using Vickers Carl Zeiss Jena NEOPHOT 21 universal indenters. Grain size and hardness tests were performed according to ASTM standards E112 and E384. For the FEM analysis, carried out with the commercial software, a 3D prosthesis model was built based on direct measurements of the fractured femoral component. To virtually analyse the effect of the incorporated geometrical feature on the prosthesis mechanical behavior under physiological loading, the computational route was based on ISO 7206-4/2002 standard, which is used to evaluate the endurance properties of femoral components of hip prostheses. Before proceeding to the simulation all unnecessary components (f.e. socket and head), which did not have significant importance from the point of view of strength of the structure and which could hinder the analysis have to be removed. Subsequently, a suitable material was defined, then attachment surfaces (model was attached to a 2/3 length of the stem) were chosen and given a load that was applied to the conical surface (3000 N). Another step was to conduct a stress analysis using SolidWorks Simulation.

Fig. 1. General view of fractured stem surface

RESULTS AND DISCUSSION

The chemical composition of tested stems is shown in Table 1. For comparison the chemical composition of the high nitrogen austenitic stainless steel according to ASTM F1586 standard (REX 734 grade) is also presented. The results of chemical analysis of the tested steel revealed, that the material of the stem, in general, fulfils the ISO standards requirements. Only the manganium and sulphur content is slightly higher than specified (see Table 1). Additionally, to confirm the chemical composition of the tested sample a SEM-EDS measurements were performed. Linear analysis enables the observation of changes in the concentrations of selected elements along the lines applied to the image topographic cross-sectional area of the sample. The results presented in Fig.2 revealed non-homogeneous distribution of alloying elements in the steel matrix.

Table 1. *Chemical composition of the stems and ASTM F1586 standard (% weight) [15]*

	C	Si	Mn	P	S	Cr	Mo	Cu	Ni	N	Nb
Rex 734 (ISO 5832-9)	0.08[a]	0.75[a]	2-4.25	0.025[a]	0.01[a]	19.5-22	2-3	0.25[a]	9-11	0.25-0.5	0.25-0.8
Sample	0.037	0.39	4.54	0.021	0.017	21.36	2.17	0.19	9.83	0.36	0.26

[a] - Maximum content

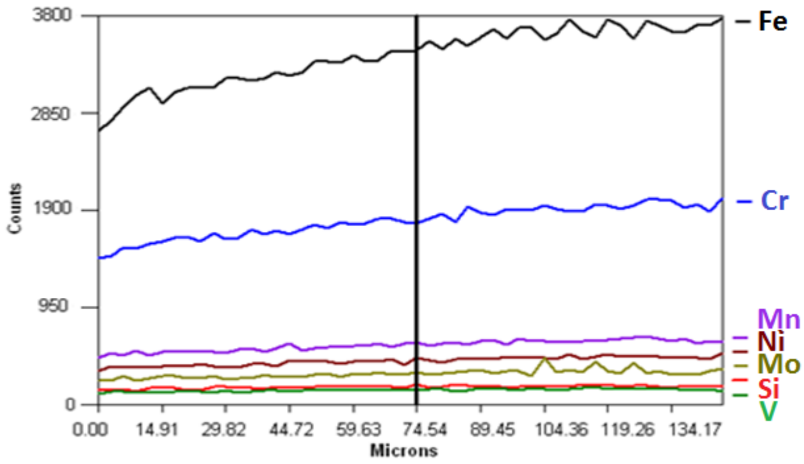

Fig. 2. SEM-EDS linear analysis of the elements concentration on the surface of the stem

The microstructure of the stem material close to the fracture has been examined. No form of corrosion such as pitting close to the point of fracture was discovered. The etched metallographic sample showed a normal equiaxed twinned austenitic grain structure (see Fig. 3). Metallurgical analysis showed excessively variable grain size with some large grains near the surface, which may reduce the fatigue properties of the austenitic stainless steel. However, mostly the grain structure in all areas was found to be homogeneous and possessed a relatively small, elongated shape, typical for a forged stainless steel. The grain size has a very significant influence on the properties of the material [16]. Appropriate determination of grain size is based on comparison of the microscopic image, counting the average number of grains per unit of area or the measurement of grain diameters randomly selected and compared the result with the respective measurement scale pattern. Recommended grain size for austenitic stainless steel used for implants is ASTM #6 or finer [17]. In this case the Jeffer's method was used. Based on photographs showing a metallographic structure of the steel was estimated amount of particles per unit area. The result is approximately 800 grains/mm^2. Based on to the American Society for Testing Materials [17] scale size is equivalent the pattern between 6 and 7. The pattern indicates for a fine – grained structure. Visual examination non-etched samples revealed carbides, which are typical for high-nitrogen stainless steel due to the nitrogen being a strong carbide former.

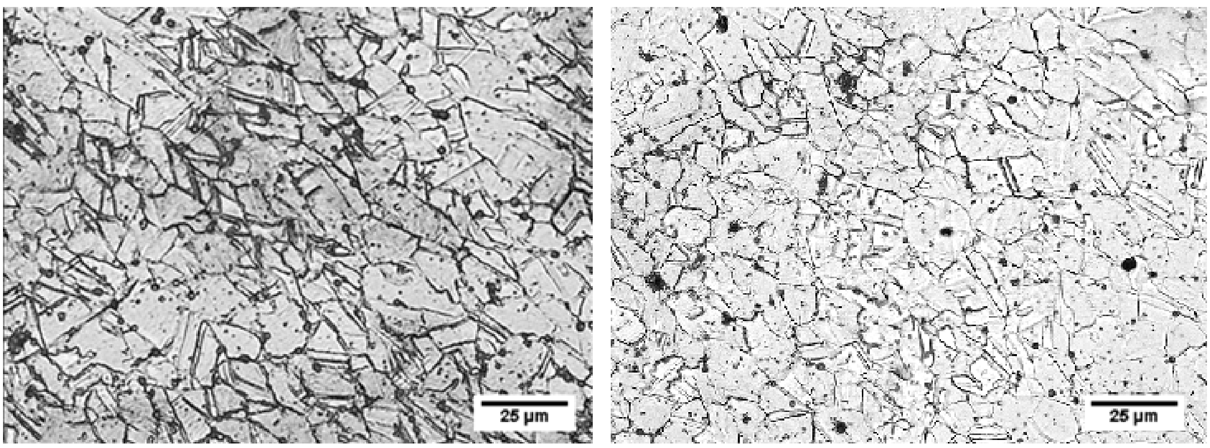

Fig. 3. Optical microscope on the femoral component micrograph of a typical austenitic matrix

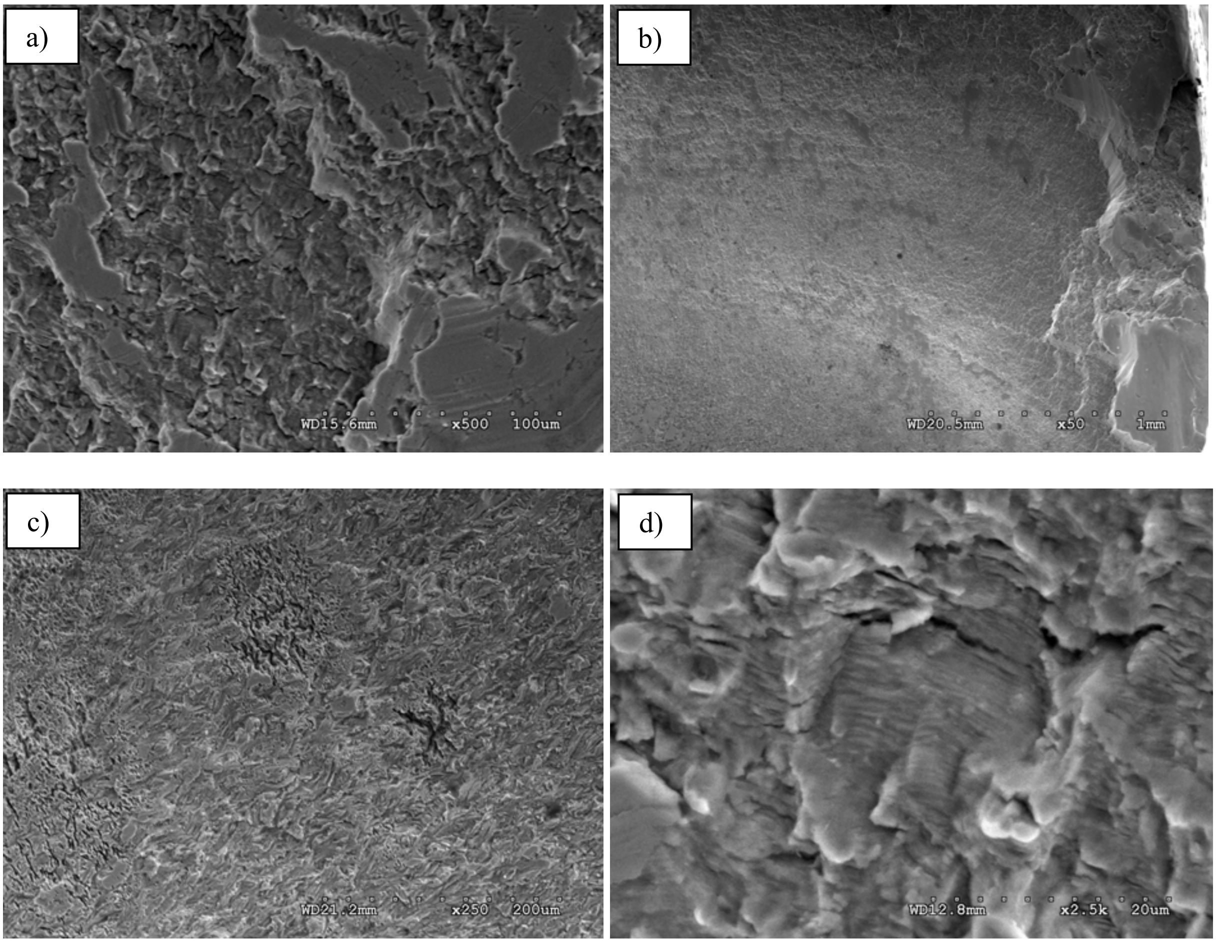

Fig. 4. Scanning electron microscopic analysis of the fracture surfaces of austenitic stainless steel failed by low cycle fatigue demonstrating: wear islands on the fracture surface (a), propagation lines (b), material discontinuities and pores (c), image of a fracture surface revealing fatigue striations (d)

Using a scanning electron microscope photographs of breakthrough examined stems were taken (see Fig.4). The study a breakthrough the fatigue area, a recess and dissection of the material due to its overload has revealed. The area of fatigue breakthrough, a multiple secondary cracks and additionally transverse cracks was clearly shown. Secondary tears (cracks) are commonly observed in fatigue failures and are created by tensile and compressive cyclic stresses induced in the material during cyclic flexing movements. There are also shown few signs of plastically deformed areas on the stem fracture surface, indicating low nominal applied stress. The study revealed the destruction, the nature of which indicates a loss of coherence. This type of fracture may be caused either by the action of a corrosive environment on the material or due to the weakening of the strength of grain boundaries by the presence of inclusions, segregation of impurities or other elements. Clear bands, also called striated fatigue, which are proof of the fact that the stem broke due to loads that caused material fatigue were not observed, due to smashed the surfaces as a result of walking after the fracture had occurred. Macroscopic fatigue striations (beach marks) were visible and created due to variances in loading parameters such as amplitude and frequency. The beach marks were closely spaced and well defined, indicating a large number of cycles to failure, which eliminated the possibility of sudden overload failure. The macroscopic analysis shows beach marks indicating crack propagation and a rough aspect commonly associated with coarse microstructure. Fatigue nucleated at the lateral part of the stem. The fatigue process commonly takes place at this site in total hip stems due to higher positive stresses under in-service loads. A fatigue crack propagated in the most of the fracture surface, leaving beach marks until the last minor part, when a final rupture can be correlated to shear lips formation. Additionally, the flattened surfaces, which may indicate that the broken prosthesis worked for a long time in the body before it was reimplnted was seen. Chafed against each other abutting surface of fractured stem deformation and abrasion have caused.

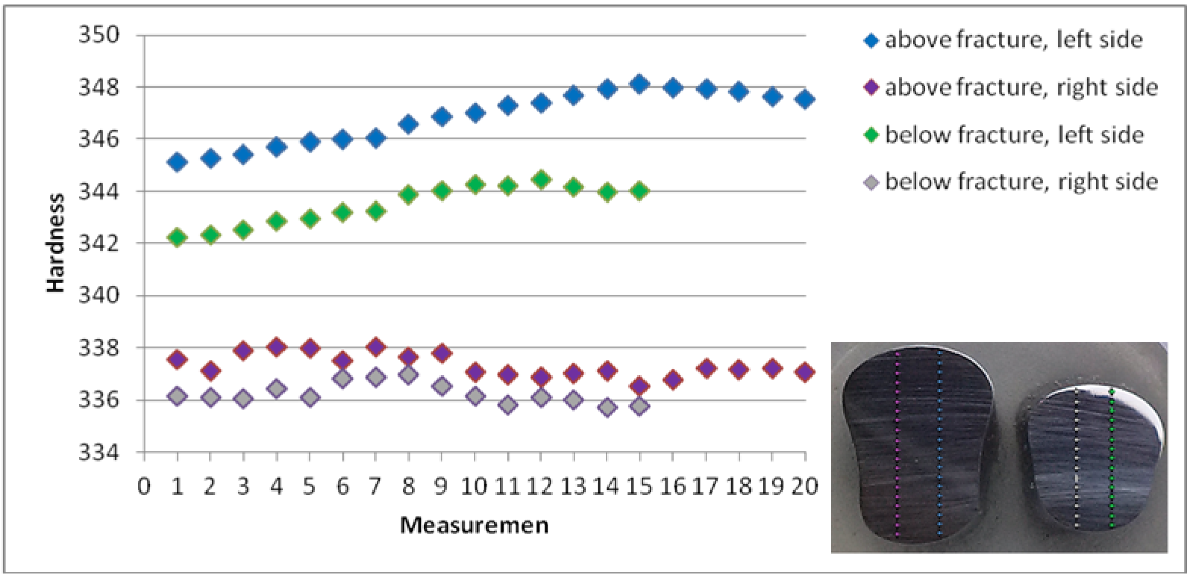

Fig. 5. Hardness measurements of the tested stem as a function of the distance from the edge of the sample

The characteristics of the mechanical properties of the samples after the surface treatment was performed on the basis of hardness measurements, by means of Vickers methods with load of 5 kg. Hardness of stem material was measured at 342 HV/5 ± 6 above the fracture and 340 HV/5 ± 4 below the fracture..The hardness average obtained of 341 HV agree with ASTM F1586 standard [16]. Hardness measurements indicate explicitly that the left side of the stem is slightly harder than the right side. This may be caused by uneven distribution of forces during plastic forming and shaping the implant or underlying reasons for this heterogeneity can be improperly carried out heat treatment.

Fig. 6. shows the results of very simple FEM calculations - the stress distribution (according to Huber von Mises hypothesis). Note, that the reduced stress level has different values, but in a place where the stresses are cumulative, the value is sevenfold greater than the yield strength of the material specified. The resultant displacement values are not large - the maximum value of deflection the neck stem under 300 kg load is less than 2 mm.

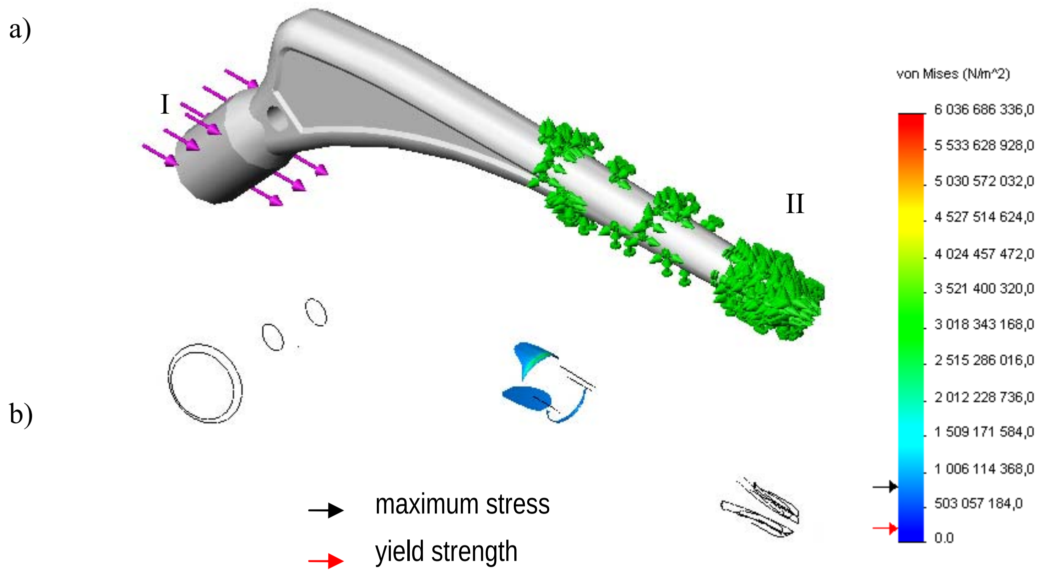

Fig. 6. 3D stem model with with marked zones of load (I) and attachment (II) (a) and zones of the largest stress tension (b).

DISCUSSION

This study evaluated the analysis of premature fatigue failure that takes place in the middle third of the height level of the cemented total hip stem. In this series of tests microstructure, hardness and analysis of chemical composition in various places of the prosthesis stem is made of high nitrogen stainless steel were conducted. The study of the chemical composition showed that this particular material does not fulfill standard. The microstructure in remote areas and close to the fracture surfaces were homogeneous and possessed a relatively small, refined grain size, typical of forged components. There were no changes caused by intergranular corrosion or pitting, which may indicate an even distribution of the major alloy components such as chromium and nickel. Metallurgical defects such as porosity and gross carbides inclusions close to the fracture sites and in remote areas were observed. The results of the microhardness revealed heterogeneity of the material. The fine grain structure confirms the greater hardness of the material, which has the effect of lowering its ductility and toughness. Pictures taken by means of a scanning electron microscope revealed the presence of pores and a plurality of recesses and delamination of the material resulting from the overload of an endurance. Examination has revealed that failure of the Centrament stem made of austenitic stainless steel was caused by fatigue crack initiation and propagation. In cracks initiation had occurred on the lateral surface of the stem [9-11], which from a biomechanical standpoint seemed to be an obvious finding because tensile stresses on a stem were expected to be highest exactly in this place. Observations of fracture surface, using scanning electron microscopy, clearly proves that the destruction of materials occurred as a result of fatigue. The fatigue process commonly takes place at this site in total hip stems due to higher positive stresses under in-service loads. A fatigue crack propagated in the most of the fracture surface, leaving beach marks until the last minor part when final rupture can be correlated to shear lips formation. High magnification analysis showed fatigue striations on the propagation surface In this case, the combination of the fatigue striation and the absence of any defects of the stem indicate that the fracture may be due simply to overloading of the stem.

CONCLUSION

This paper reports the hip stems analyzed experienced a premature catastrophic fatigue fracture, nucleated at the lateral region. The failure was promoted by microstructural defects harmful to the fatigue performance. Any slight discontinuity or defect on this section of the surface acted as a preferential site to nucleate a crack which was propagated by the fatigue mechanism. The stems were produced with ASTM F1586 (REX 743 austenitic stainless steel, which is not in conform with ISO 5832-1 standard, that describes the requirements for mechanical resistance, chemical composition and microstructure for medical devices.

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