Engineering Failure Analysis 72 (2017) 1–10

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Analysis of microstructural aspects of a hip stem failure made of the REX 734 stainless steel

Zbigniew Oksiuta [a,*], Zbigniew Mazurkiewicz [b], Eliza Romanczuk [a], Marcin Andrzejewicz [b], Agnieszka Krawczynska [c]

[a] Bialystok University of Technology, Faculty of Mechanical Engineering, Poland
[b] Regional Hospital of J. Sniadecki, Bialystok, Poland
[c] Warsaw University of Technology, Faculty of Materials Science, Poland

ARTICLE INFO

Article history:
Received 21 May 2016
Received in revised form 18 October 2016
Accepted 14 November 2016
Available online 15 November 2016

Keywords:
Failure mechanism
Stainless steels
Corrosion
Mechanical testing
Chemical analysis

ABSTRACT

In this work we described the microstructure, mechanical and corrosion investigations of two total hip prostheses with cemented stems that were broken after relatively short period of implantation, ~3.5 years. The fractured stems were made of the REX 734 austenitic stainless steel, a modified version of the 316 L(V) grade. The REX 734 steel has, in comparison to the 316 L steel, lower content of nickel and higher amount of chromium, nitrogen and niobium. Broken metal endoprosthesis were removed from female patients with body mass index of 27.1 and 29.7. No discontinuity and defects on the prosthesis surface were observed. Radiographs obtained after failure revealed a lack of a cement fixation at the proximal part of the stem. Thus, a probable reason of the failure was a stem loosening at proximal part caused by differences of a tissue density of the proximal and distal part of femoral bone. Comprehensive microstructure observations revealed that in both cases the fatigue fracture was initiated at an anteromedial part of the stems. Failure initiation of both stems could be initiated by large niobium carbides detected in the microstructure of the stems. Despite coarse NbC precipitations, size up to 0.3 μm, the microstructure and corrosion properties of the broken stems made of REX 734 steel fulfil ISO (ASTM) standards.

1. Introduction

Austenitic stainless steels are very popular material used for implants and surgical instruments. AISI 316 L(V) (ISO 5832-1) austenitic stainless steel and the comparable REX 734 (ISO 5832-9) grade are also used in the cemented total hip arthroplasty. Appropriate mechanical properties, biocompatibility and relatively low cost of production make these austenitic alloys very attractive materials for aforementioned applications [1,2]. It is known that the REX 734 grade is a modified version of the 316 L(V) steel, with lower nickel and higher chromium, nitrogen and niobium content. Careful selection of the alloying elements towards decreasing nickel content ensures improvement of mechanical properties and corrosion resistance, and makes the REX 734 alloy more favourable than 316 L grade [3].

Regarding chemical composition it is well known that nitrogen is a strong austenite stabilizer, reduces of the strain-induced martensite transformation and has greater solubility in the austenite steel matrix than carbon [4,5]. Nitrogen is also an important

* Corresponding author.
E-mail addresses: z.oksiuta@pb.edu.pl (Z. Oksiuta), zsmazurkiewcz@wp.pl (Z. Mazurkiewicz), e.romanczuk@doktoranci.pb.edu.pl (E. Romanczuk), ortopedia@sniadecja.pl (M. Andrzejewicz), a.krawczynska@inmat.pw.edu.pl (A. Krawczynska).

http://dx.doi.org/10.1016/j.engfailanal.2016.11.012
1350-6307/

alloying element in terms of corrosion resistance and mechanical properties improvement, and replaces nickel with cost reduction [6]. Another benefit of nitrogen addition is an improvement of the stacking fault energy and that together with molybdenum enhance fatigue properties of the stainless steel [7]. Niobium and tantalum are added since these elements have a stronger tendency to form carbides that avoid detrimental effect of chromium carbide precipitations on the intergranular corrosion properties in austenitic steels. Also, titanium and niobium are elements that suppress the sensitivity of pitting corrosion in stainless steels.

On the other hand vanadium, tantalum, niobium and titanium elements cannot be added in significant amounts to the stainless steel, as they are major brittle nitride and carbide former.

Prior to surgical operation all parts of the artificial hip endoprosthesis are sufficiently tested and sterilized, however, it has been reported that stem fracture may occur. There are many probable possibilities for the hip stems fractures. From the statistical point of view, an isolated fracture of the femoral hip stem is not a frequent issue; however there are literature data where stems made of 316 L(V) stainless steels, after relatively short time of exposure, about 5 years or shorter, were broken [8–12].

In this work, we analysed two femoral cemented stems made of the REX 734 austenitic stainless steel (ISO 5835-9, ASTM F 1586) that fractured after short period of implantation. Since revision of the fractured stem from the femur is difficult and time consuming surgery, and has also detrimental influence on the femoral bone of the patient, the main goal of this study was to find out a plausible explanation about the fractures of hip stems made of the REX 734 steel.

The microstructure and other properties of the early fractured hip stems made of the REX 734 steel were also characterized and compared with the 316 L(V) steel tested in the same conditions.

2. Materials and methods

After surgical revision, two broken parts of both hip stems were prepared for microstructure observations, mechanical testing, Vickers hardness measurements and corrosion resistance analysis. Microstructural observations of the material were carried out by an optical microscope (OM) Nikon Eclipse LV1000. The fractured surfaces were examined by means of a scanning electron microscopy (SEM) Hitachi S-3000N, equipped with an energy dispersive X-ray spectroscopy (EDS). Microstructural characterisations were performed by a transmission electron microscope (TEM) JEOL 1200 and by a scanning transmission electron microscopy (STEM) Hitachi S-5500 equipped with an EDS detector.

Chemical composition of the stems was examined by a spark emission spectroscopy (Thermo ARL Quantris, Switzerland). Qualitative phase structure of the broken stems was determined using a Bruker D8 Advanced X-ray diffractometer (XRD) with the Cu-Kα radiation ($\lambda = 1.5498$ Å). Quantitative metallographic investigations of the grain size were performed using the MET–ILO3.0 computer program.

Potentiodynamic corrosion tests were performed according to the ASTM G48 standard in the 0.9% sodium chloride (NaCl) solution in a three-electrode electrolytic cell consisting of a platinum electrode as counter electrode, a saturated calomel electrode as reference electrode and a sample as working electrode. The corrosion resistance (Rp), the corrosion potential (E_{cor}), the current corrosion density (I_{cor}), the corrosion rate (C_R), the breakdown potential (E_b) and the repassivation potential (E_{cp}) were determined.

Small punch tests (SP) were carried out using a universal testing machine Zwick/Roell Z010 at a speed of traverse of 8.0×10^{-3} mm s^{-1} at room temperature. Three to five disc-shaped specimens with 3.0 mm in diameter and thickness of 0.25 ± 0.05 mm were extracted from the broken stems close to the fractured area followed by grinding using SiC abrasive paper. Hardened 1.0 mm in diameter steel ball was used as a puncher.

Nanoindentation measurements in a cross section of the stems in both perpendicular directions were conducted using Vickers indenter with a load of 0.1 kg. Each indent was at the same distance in a row. The experiment was carried out using an UNHT CSM Ultra-Nanoindentation Tester equipped with an atomic force microscope (AFM). Constant displacement mode was used to ensure stable indentation depth. The hardness and Young modulus data presented here are an average of 10 indents.

3. Results and discussion

3.1. Fracture analysis of hip stems

Two collarless cemented hip stems were removed from female patients after ~3.5 years of implantation. Patients of 65/78 kg weight were active and had body mass index (BMI) of 27.1 and 29.7, respectively. Standard radiographs obtained after fracture, presented in Fig. 1, show a gap at the proximal part of the stem (the arrow 3 in Fig. 1b). The main reason for failure was the stem loosening at the proximal part, probably caused by differences of tissue density between the proximal and distal part of the femoral bone or by the lack of adequate cement fixation. Arrows 1 and 2 in Fig. 1 correspond to the place of the femoral implant fracture. Note that the distal fixation of the stems remained rigid.

The broken stems were taken for further microstructure analysis. Prior to investigations, both parts of the stems were sterilized.

Exemplary view of the fractured stems is presented in Fig. 2. It is interested to note, that both stems were broken off at the same location in a half of a distal of their lengths. Macroscopic observations of the stems after removal did not reveal any evidence of the corrosion or mechanical scratching generated on the surface during the surgical operation. Few unimportant scratches at the proximal and distal parts of the stems were observed, probably as a result of the revision surgery.