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Intergranular Corrosion-Fatigue Failure of Cobalt-Alloy Femoral Stems

A FAILURE ANALYSIS OF TWO IMPLANTS*

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ABSTRACT: Two modular hip implants with a cobalt-alloy head and a cobalt-alloy stem were retrieved after a fracture had occurred in the neck region of the femoral component, eighty-five and seventy months after implantation. Both implants failed less than one millimeter distal to the taper junction between the head and the stem (outside of the taper). The fracture surfaces of the implant were investigated with the use of scanning electron microscopy, to determine the nature of the failure process. The fractures occurred at the grain boundaries of the microstructure and appeared to be the result of three factors: porosity at the grain boundaries; intergranular corrosive attack, initiated both at the head-neck taper and at the free surface; and cyclic fatigue-loading of the stem. The corrosive attack of the free surface was initiated, in part, by the egression of surface grains and by the ingression of fluid into the intergranular regions. Sectioned surfaces showed extensive intergranular corrosive attack in the prosthetic neck localized in the region of the head-neck taper junction and penetrating deeply into the microstructure.

Recent reports[1,3,4,6,8] have indicated that a corrosive attack can occur in the taper crevice of modular implants made of similar metals or of mixed-metal combinations. On the basis of these observations, it has been speculated that the corrosive attack, while resulting in metal release[9], may lead to mechanical failure of the component. Gilbert et al.[6] and Buckley et al. reported that one of several corrosion mechanisms observed in the taper region was intergranular attack in implants that had a cobalt-alloy head coupled with a cobalt-alloy stem. In one prosthesis, this intergranular attack had penetrated as much as five millimeters deep from the surface of the neck region of the taper. It is possible that this corrosive attack may have ramifications with regard to the structural integrity of implants and may contribute to fracture in the neck region of hip prostheses. This observation has not been reported or demonstrated in the literature to our knowledge.

Recently, two modular total hip prostheses, consisting of a wrought cobalt-alloy (ASTM F799) head coupled with a wrought cobalt-alloy stem, were received in the implant retrieval laboratory at Rush-Presbyterian-St. Luke's Medical Center after revisions had been performed to replace the fractured components. Both of the fractures had occurred in the neck, just distal to the head-neck taper. We present the results of a detailed fractographic and electron microscopic analysis of the region in which these prostheses had failed.

Case Reports

CASE 1. A 112-kilogram, 175-centimeter-tall man had a primary total hip replacement with the insertion of a PCA prosthesis (Howmedica, Rutherford, New Jersey) without cement, at the age of sixty-seven years, for the treatment of severe osteoarthrosis (Fig. 1-A). Seventy months postoperatively, the patient was seen by one of us (M. R. Z.) because of the sudden onset of pain in the hip. Before this, the hip had been asymptomatic. The patient had had an active lifestyle and had frequently played golf. Radiographs revealed a fractured prosthetic neck (Fig. 1-B).

At the revision, the prosthetic fracture was easily identified, and the prosthetic head was free in the joint. The femoral component was extremely well fixed to the adjacent bone and was difficult to extract. On removal, an extensive amount of bone was adherent to the device, and a fracture of the femoral shaft was sustained intraoperatively. The acetabular component was well fixed. A long-stem prosthesis was inserted without cement and with the use of strut allografts. The patient was doing well two years postoperatively.

CASE 2. A 111-kilogram, 178-centimeter-tall man was managed, at the age of forty-nine years, with a primary total hip replacement with the insertion of a PCA prosthesis (Howmedica) without cement, for end-stage osteoarthrosis of the right hip. The postoperative course was uneventful with the exception of mild pain in the lateral aspect of

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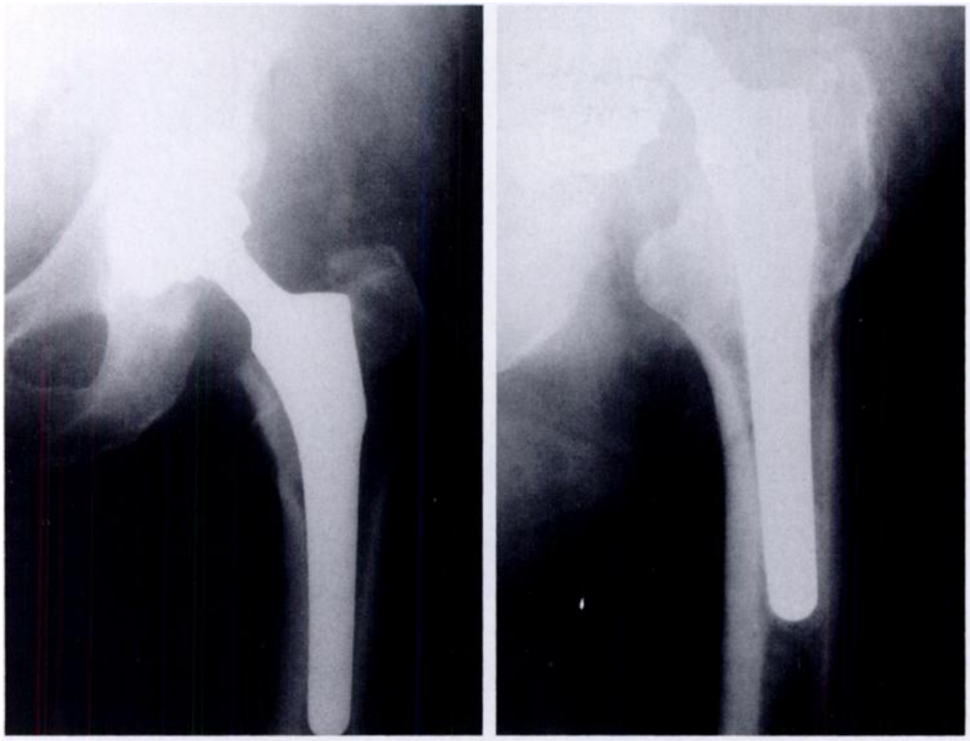

FIG. 1-A FIG. 1-B

Figs. 1-A and 1-B: Case 1. Clinical anteroposterior radiographs.
Fig. 1-A: Postoperative radiograph.
Fig. 1-B: Seventy months postoperatively, the fractured prosthetic neck is clearly seen just distal to the head-neck junction.

the thigh since the arthroplasty. The patient was active and performed moderately strenuous manual labor that required him to ascend and descend stairs frequently.

Eighty-five months postoperatively, the patient was seen in the emergency room by one of us (K. C. B.), because of an acute onset of severe pain in the right hip and an inability to bear weight on the right lower extremity. Just before the onset of the pain, the patient had noted a loud snap when he was bending over while mowing his lawn. He stated that for three weeks before this incident the pain in the thigh had been slightly worse. He recalled no specific traumatic event leading to the current, acute symptoms. Radiographs revealed a fractured prosthetic femoral neck (Fig. 2).

At the revision, the fracture of the femoral component was readily identified. There was chronic granulomatous tissue within the joint capsule, but there was no evidence of metallic tissue-staining. The femoral component was well fixed and difficult to extract. The acetabular component was also well fixed, but, because of substantial polyethylene wear, it was also removed. A revision total hip replacement was done without cement. The patient was minimally symptomatic seven months postoperatively.

Materials and Methods

After retrieval, the implants were cleaned and prepared for analysis. The prostheses were sectioned with a water-cooled, high-speed cut-off wheel to expose the modular taper junction and so that the microstructure and intergranular attack in the region of the neck could be observed. The fracture surfaces were not altered in Case 2, but they were sectioned in Case 1.

The sectioned surfaces were ground and polished, with the use of a water suspension of alumina, down to 0.3 micrometer. No etching was used at any time. The fracture surfaces were cleaned ultrasonically in ethanol

FIG. 2

Case 2. Clinical anteroposterior radiograph showing the fractured prosthesis eighty-five months postoperatively.

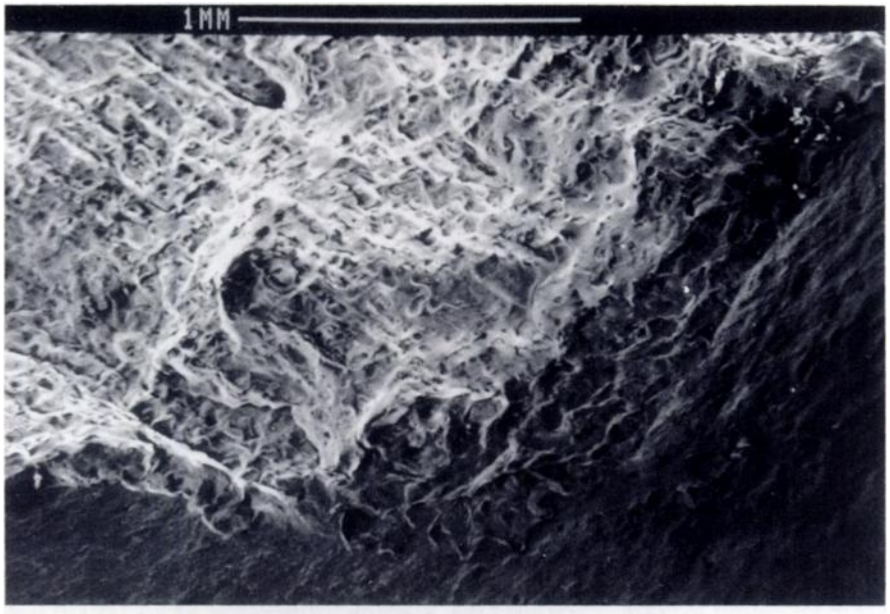

FIG. 3

Case 1. Low-magnification micrograph of the edge of the fracture surface, showing the intergranular nature of the fracture. The fracture surface at the superior initiation point is at the upper left, and the free surface of the neck is at the lower right. Intergranular pores are present on the fracture surface (× 41.8).

or a dilute sodium-hypochlorite solution, or both, followed by an acetone rinse. These solutions did not alter the metal surface in any way. Scanning electron microscopy was then performed on the surfaces.

Results

Both fractures had occurred in the neck region, just outside of the taper junction between the head and neck components. The fractures had begun at or near the most superior region just outside of the taper-free surface junction and had propagated toward the inferomedial side, parallel to the taper junction.

Analysis of the Fracture Surfaces

For Case 1, a low-magnification scanning electron micrograph of the superolateral fracture surface (Fig. 3) showed that the fracture surface had a smooth appearance, with small pores or craters. As will be subsequently shown, this appearance was due to interconnected and isolated porosity as well as a corrosive attack at the

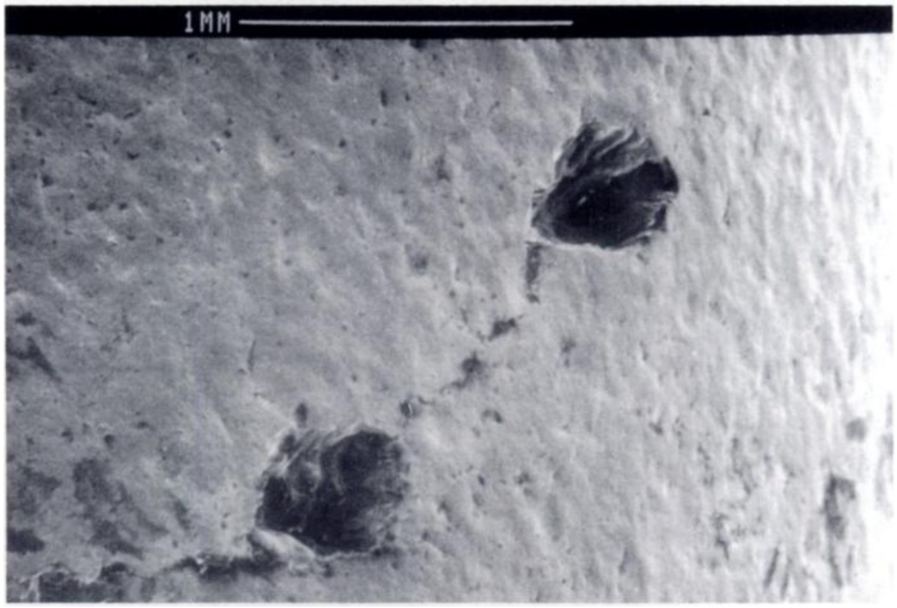

FIG. 4

Case 1. Low-magnification micrograph of the free surface, showing pits that have formed because of egression of small surface grains. These small grains are located at the larger grain boundaries (× 40.8).

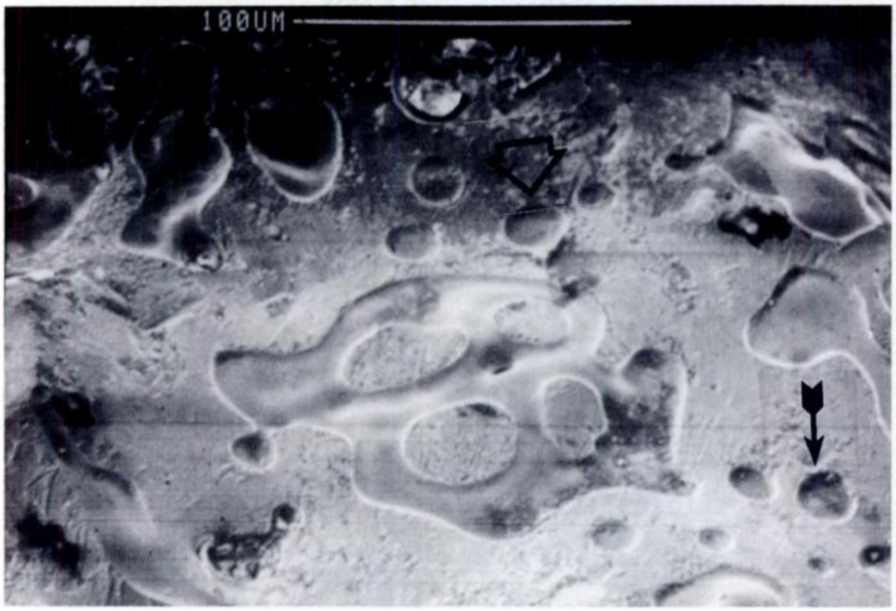

FIG. 5-A

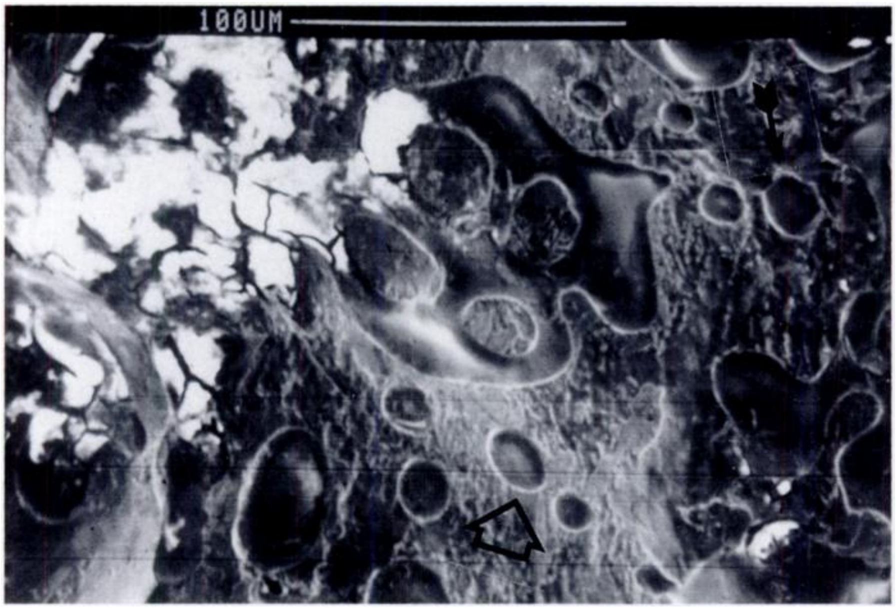

FIG. 5-B

Figs. 5-A and 5-B: Case 2. Micrographs of the opposing fracture surfaces, showing the smooth and rough regions. Note the mirror symmetry, from top to bottom, of the two figures. The pores (arrows) appear to be isolated by the rough regions, indicating that they were present before the fracture of the prosthesis. Some non-conducting debris, which is rich in chromium and most likely consists of segregated carbides at the grain boundaries, can be seen (Fig. 5-B, upper left) (× 406 [Fig. 5-A] and × 400 [Fig. 5-B]).

grain boundaries of the microstructure.

Intergranular cracks were seen to connect several pits that had formed on the outer surface of the prosthesis (Fig. 4). These pits, which were as large as 500 micrometers in diameter, were small surface grains that had fractured about their boundaries and had egressed out of the surface microstructure. These small egressed grains were typically located at the larger-grain boundaries.

The appearances of the fracture surfaces were similar for the two retrieved implants. Micrographs of Case 2 (Figs. 5-A and 5-B), made about one millimeter from the lateral free surface (that is, at the site at which the fracture had initiated), showed two general regions of interest: one smooth and one rough. The rough regions appeared to be deformed, to show clear evidence of pitting corrosion attack, and to indicate that the grain boundaries in these regions were initially intact but had subsequently been attacked by the combined effects of the repeated cyclic loading and the intergranularly penetrating fluid. The smooth regions appeared to be slightly depressed from the rough regions and were irregular in shape. These smooth regions may have been due either to an initial intergranular corrosive attack,

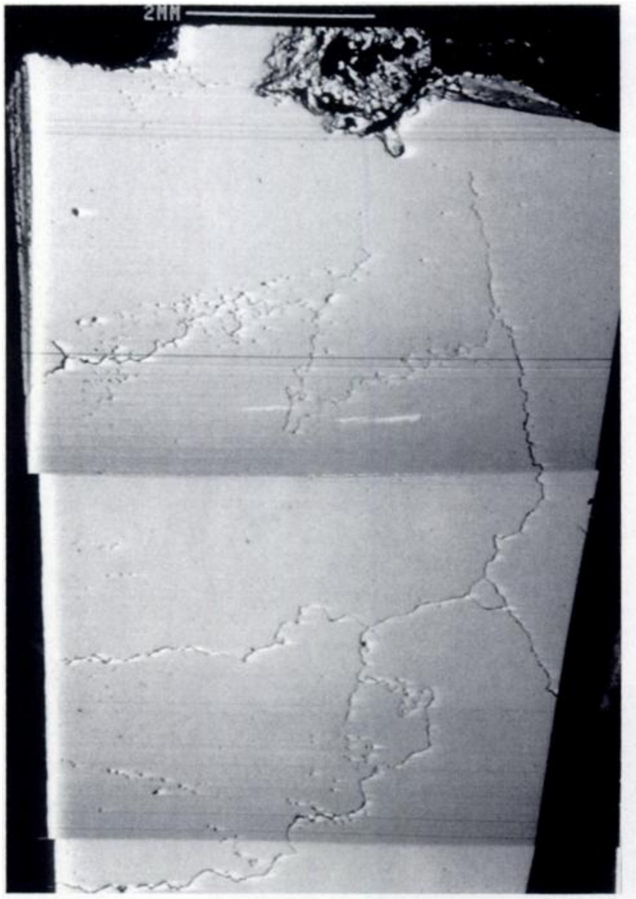

FIG. 6

Case 1. Montage of the cross section, with the fracture surface at the top and the laterosuperior surface at the left, showing intergranular cracks throughout the neck. The fracture surface follows the grain boundaries of the material.

during which the penetrating fluid created smooth pathways or, alternatively, to porosity at the grain boundaries that had existed before the corrosive attack and thus was the result of the manufacturing conditions used to make the prosthesis.

In order to determine if the smooth regions were the result of formation of pores during the manufacture of the prosthesis or the result of fluid penetration, it was necessary to find the corresponding regions on each fracture surface from one implant (that is, to locate the mirror image of one fracture site on the opposite fracture surface). Then, if there were regions in which pores were not interconnected but rather isolated by the rough regions (indicating that the grain regions had been initially intact), it could be assumed that the pores probably had been present before the intergranular attack and were therefore the result of porosity formation during the manufacture of the prosthesis.

This analysis was carried out for Case 2. Micrographs with mirror symmetry, from top to bottom, of the same region on opposing fracture surfaces (Figs. 5-A and 5-B) showed several isolated, roughly circular pores that had no signs of being interconnected but were, instead, only surrounded by a rough fracture surface. This suggests that the pores were not created by fluid penetrating along the grain boundaries but were instead generated during the manufacture of the prosthesis.

Analysis of the Sectioned Surfaces

The sections from the necks revealed clear evidence of corrosive penetration of fluid intergranularly into the microstructure. This intergranular attack was adjacent to the fracture surface and was continuous with an intergranular attack emanating from the head-neck taper region. In a montage of a sectioned surface from Case 1 (Fig. 6), the outline of the grains was seen clearly and was the result of intergranular attack and porosity. For Case 2, the neck-head taper junction was seen clearly and had been extensively attacked at the grain boundaries (Fig. 7). The intergranular attack seemed to be concentrated at the superior and inferior surfaces of the neck at the taper-free surface junction.

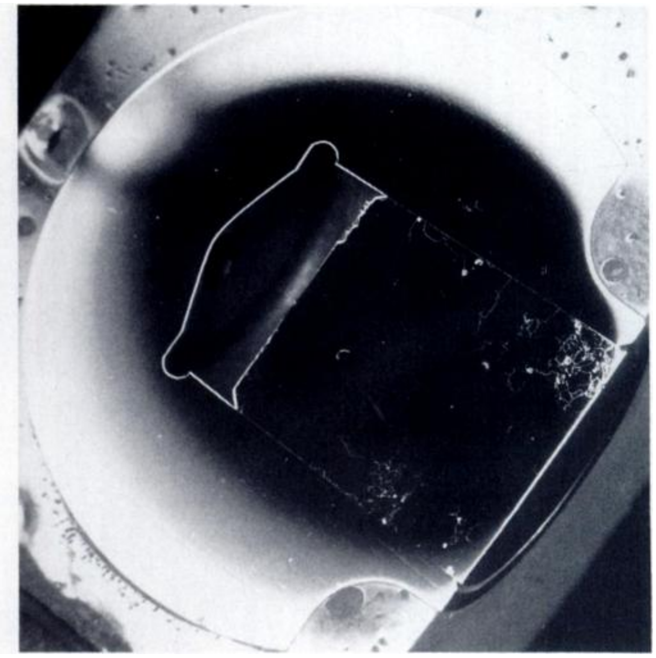

FIG. 7

Case 2. Optical photograph showing intergranular cracking at the taper-free surface junction. This cracking, which is localized at the taper junction, appears to travel down into the neck toward the region of the fracture surface.

Discussion

The scanning electron microscopy revealed evidence of corrosion-fatigue fracture of the femoral neck in two similar-metal (cobalt-alloy head and cobalt-alloy stem) modular hip prostheses. In both patients, considerable time had elapsed before failure (seventy and eighty-five months), indicating a process that required time to evolve to the failure point. In addition, both patients were heavy and quite active; thus, they placed considerable mechanical demands on the prostheses.

The granulomatous reaction seen in Case 2 was similar to that reported by Mathiesen et al., in a severely corroded modular hip prosthesis consisting of a cobalt-alloy stem and a cobalt-alloy head, and the reaction could be the result of metal-ion release.

Furthermore, an intergranular corrosive attack was shown to have occurred in the neck region, at the lateral and medial sites of the head-neck taper junction, and this intergranular attack had penetrated several millimeters into the microstructure. In Case 2, the intergranular cracking was focused at the taper junction and had penetrated into the microstructure.

Several factors may have contributed to this failure process. Porosity was present at the grain boundaries in both implants, and this porosity may have resulted from manufacturing conditions; most likely, it had not been created by corrosion. This was determined by observation of the opposite sides of the same fracture site and the location of regions with isolated pores that could not have been the result of a penetrating corrosive attack (if they had, they would have been interconnected).

During the manufacture of these prostheses, a porous coating of beads is sintered to the surface of the femoral component. To do this, the temperature of the device has to be raised to near the melting point. This incipient melting condition makes it very likely that diffusional processes are ongoing, so that it is possible for vacancy motion and void formation to occur at the grain boundaries. Also, the sintering process facilitates alloy segregations[1,2,6,7], which may further weaken the grain boundary regions.

Mechanically assisted crevice corrosion[1,6] also appears to have contributed to the fracture process. In the two implants, the intergranular corrosion, which had started both in the head-neck taper region and at the free surface where egression of grains had occurred[5], had extended intergranularly throughout the microstructure near the fracture region and had weakened the grain-boundary material further. When this was compounded by crack propagation induced by the cyclic loading stresses, the combination of factors eventually created a large enough crack to fracture the neck.

In conclusion, a combination of factors appears to have contributed to the intergranular fractures of the prosthetic necks. An intergranular corrosive attack of the microstructure of the neck starting at the taper and at sites of grain egression, in conjunction with fatigue loading, resulted in the intergranular corrosion-fatigue fractures. Also, conditions for manufacturing of the femoral component may have resulted in intergranular porosity, which may have further weakened the prosthesis and provided a pathway for intergranular attack.

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