Effects of prosthesis surface roughness on the failure process of cemented hip implants after stem–cement debonding

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Abstract: Retrieval studies suggest that the loosening process of the cemented femoral components of total hip arthroplasties is initiated by failure of the bond between the prosthesis and the cement mantle. Finite element (FE) analyses have demonstrated that stem–cement debonding has stress-producing effects in the cement mantle. High interface friction, which corresponds to a degree of surface roughness, reduces these stresses. In experiments, however, debonded rough stems produced more cement damage than polished ones; in the Swedish Hip Register polished stems were clinically superior with respect to stems with a mat surface finish. The purpose of the present study was to investigate this contradiction. For this purpose, global and local FE models with debonded stem–cement interfaces were used to study the effects of prosthesis surface roughness on the cement stresses on a global scale and microscale, respectively. Similar to earlier numerical studies, the global FE model predicted that an increased surface roughness of the stem reduced the stresses in the cement mantle. The local model provided insight in the load-transfer mechanism on a microscale and could explain the experimental and clinical findings. The local cement peak stresses around the asperities of the surface roughness profile increased with increasing surface roughness and decreased again beyond a particular roughness value. Cement abrasion is caused by localized stresses in combination with micromotion. From this study it can be concluded that to minimize cement abrasion, debonded stems should either have a polished microstructure to minimize the local cement stresses or have a profiled macrostructure to minimize micromotions at the stem–cement interface. © 1998 John Wiley & Sons, Inc. J Biomed Mater Res, 42, 554–559, 1998.

Key words: surface roughness; prosthesis; cement mantle; stem–cement debonding; total hip arthroplasty

INTRODUCTION

Aseptic loosening has been identified as the main failure mechanism of cemented total hip arthroplasties (THA). Harris suggested that the loosening process of the femoral component is initiated by failure of the bond between the prosthesis and the cement mantle. This suggestion was based on extensive retrieval studies that showed sites of stem–cement debonding in every specimen early after implantation. Experimental studies and numerical finite element (FE) analyses have demonstrated that stem–cement debonding increases cement stresses and therefore can accelerate the failure process of the reconstruction. This stress-producing effect of debonding may be reduced by increased friction at the stem–cement interface, which can be accomplished by increasing the prosthetic surface roughness. Hence, it can be hypothesized that debonded stems should have a rough surface to minimize cement damage. However, in an earlier article we reported on laboratory experiments that showed the opposite: debonded rough stems produced more cement damage than polished ones. Clinically similar phenomena have been found in the Swedish Hip Register; the polished Exeter stem was shown to be clinically superior to the Exeter stem with a rougher surface finish. Hence, the FE analyses seem to contradict the experimental studies and the clinical findings. The purpose of the present study was to investigate this contradiction.

For this purpose, global and local FE models were used to study the effects of prosthesis surface roughness on the cement stresses on a global scale and a microscale, respectively. It was investigated whether the experimental and clinical findings could be explained by the FE analyses.

MATERIALS AND METHODS

The FE analyses were performed in three steps (Fig. 1). In step 1 2-dimensional (2-D) FE analyses were performed to
relate the surface roughness value \( R_a \) to a coefficient of friction \( \mu \). This information was necessary because in the stress analysers with the global models the surface roughness was represented by a coefficient of friction only. In step 2 the effects of surface roughness on the cement stresses in a global sense were determined. In addition, displacement patterns were obtained in step 2 that were applied to a local model to analyze the effects of surface roughness on the local stresses in the cement mantle (step 3). In this way the relation between the surface roughness value and local cement stress was established.

**Step 1**

The relation between the roughness value and the coefficient of friction was determined using 2-D FE models consisting of metal and cement segments pressed against each other (Fig. 2). Plane strain quadrilateral elements were used in the model and the unbonded, frictionless metal–cement contact was simulated using special gap elements (MARC Analysis Research Corporation, Palo Alto, CA). A compressive force \( N \) was applied to the prosthetic segment perpendicular to the unbonded metal–cement interface (Fig. 2). While keeping the cement segment in place at the bottom, the tangential force on the metal section \( F \) was increased until the prosthetic segment started to slip over the cement. The global coefficient of friction at the interface was determined by the ratio of the tangential force \( F \) and the compressive force \( N \). The global surface roughness value \( R_a \) of the metal was varied between 0 and 30 \( \mu m \) and was modeled as sinusoidal surface profiles (Fig. 2). As a consequence of the definition of the \( R_a \) value, the same surface roughness value can be obtained with a varying number of surface asperities. This phenomenon was included in the study by modeling surface roughness profiles with 2.5 and 5 sines for every surface roughness value considered. In this 2-D model the coefficient of friction was assumed to depend solely on the shape of the two segments without consideration of adhesive forces or additional microroughness. Hence, a flat surface led to a frictionless metal–cement interface.

**Step 2**

The global FE model simulates laboratory experiments reported earlier. It simulates an axisymmetric tapered stem pushed into a cement mantle. In the FE simulation a force of 50 N was applied to the top of the stem, and the cement mantle was distally constrained in the axial direction. The FE model consisted of 542 axisymmetric quadrilateral elements (Fig. 3). To simulate frictional stem–cement interface conditions, gap elements were situated at the interface. The amount of friction was varied, depending on the surface roughness value to be studied. The relation between the roughness value and maximal Von Mises stress in the cement mantle was determined, and the displacements of the global nodes were recorded.

**Step 3**

The local FE model represented a detail of the global one as an area at the stem–cement interface (Fig. 3). One cement and one prosthetic element in the tip region of the global model were subdivided into 1550 axisymmetric quadrilateral elements, resulting in a refined axisymmetric FE model of the interface area (Fig. 3). Hence, stress patterns on a microscale can be obtained with this model. The interface had a length of 2.2 mm, and the 63 interfacial points were relocated in a sinusoidal wave pattern to represent a prosthesis surface with a specific roughness value. Frictionless gap elements were used to simulate nonlinear contact at the unbonded interface. Hence, friction at the interface was only generated by the surface profile of the stem. The displacement values determined in step 2 with the global model were used as boundary conditions for the corresponding nodal point in the local model. These boundary conditions were interpolated between the corner nodes, resulting in straight exterior edges of the local model. These interpla-
tions may introduce stress artifacts in the vicinity of the nodal points where the displacements are applied. For this reason, the results were only considered in a "region of interest" remote from these nodal points (see Fig. 3).

For all models the same mechanical properties for the cement and metal were used and were assumed to behave in a linear elastic and isotropic manner. The Young's modulus for the cement material was set at 2.2 GPa and Poisson's ratio at 0.3. The prosthesis was assumed to be made out of stainless steel with an elastic modulus of 200 GPa and a Poisson's ratio of 0.28.

RESULTS

The 2-D analysis showed that friction increased linearly with roughness and with the number of asperities modeled at the interface (Fig. 4). Due to the assumption that friction was caused by roughness only, the ideally smooth case ($R_a = 0.0$) led to a friction coefficient of 0.0. When 2.5 sines were modeled at the interface, a roughness value of 20 μm resulted in a coefficient of friction of 0.25. Assuming the same roughness value but modeling with more asperities resulted in a surface profile with higher gradients and hence steeper asperities. This explains why the coefficient of friction increased with more asperities.

In the global model the cement stresses generated in the cement mantle were predominantly oriented in the circumferential direction and were reduced by surface roughness (Figs. 5, 6). After load application the stem subsided in the cement mantle, thereby stretching the cement mantle and creating tensile hoop stresses. Hence, stress level and subsidence were closely related. Maximal cement stresses were generated in the vicinity of the interface, particularly near the tip of the

Figure 3. The global FE mesh representing a taper shaped stem forced into a cement mantle. The local mesh is a detail of the global one and facilitates stress calculations and the effects of surface roughness on a microscale.

Figure 4. The relationship between surface roughness ($R_a$ value) and the calculated friction coefficient.

Figure 5. Von Mises stress patterns in the cement mantle around the stem with a surface roughness of 0.0, 5.0, and 15.0 (from left to right) calculated with the global model.
stem. The maximal peak cement stress was about 1.2 MPa for the ideally smooth (frictionless) surface. Cement peak stresses were reduced with about 50% for the roughness value of 5 μm. More sines modeled at the interface of the 2-D local model resulted in a higher coefficient of friction, which explains that for a particular roughness value lower cement stresses are generated in those cases (Fig. 6).

On a microscale the stem surface generated cement stress peaks at the asperities of the roughness profiles. These local cement peak stresses increased with increasing surface roughness and decreased again after a particular surface roughness (Figs. 7, 8). Assuming ideally smooth surfaces, the cement stresses were rather uniformly distributed over the interface and in the cement mantle (Fig. 7). The maximal cement stress peak in this case was 1.2 MPa, which is almost identical to the one generated in the global model. This indicates that the boundary conditions derived from the global model were correctly applied to the local

one. In contrast with the results found with the global model where cement stresses decreased with surface roughness, the local model predicted an increase of peak cement stresses with increasing surface roughness. The values of these local cement stresses were considerably higher than those found in the global analyses. When 5 sines were modeled at the interface, the peak cement stress increased with roughness up to a roughness value of about 15 μm. Beyond this roughness value the peak value of the cement stress decreased again (Fig. 8).

The finding that the stresses around the asperities first increased with the roughness value but decreased again beyond a certain roughness value can be explained by analyzing how the external axial load is transferred from the stem to the cement (Fig. 9). Because it is assumed that the unbonded interface in the local model is frictionless, only compressive stresses are generated at the interface, which have to balance the external load. Because the external load is oriented in the axial direction, only the axial component of the

Figure 6. The effect of surface roughness (Ra value) on the maximal Von Mises stress calculated in the global model.

Figure 7. Von Mises stress patterns in the cement mantle calculated with the local model. Surface roughness values are 0.0, 5.0, 15.0, and 30.0 (from left to right).

Figure 8. The relationship between surface roughness (Ra value) and the maximal Von Mises stresses in the local model.

Figure 9. Schematic presentation showing that an effective axial load transfer can be obtained with profiled stems (right). However, when the profiles are relatively shallow, the axial load transfer becomes less effective and the profiles will act as stress inducers (middle). With a smooth surface an axial load transfer is ineffective, but local stress peaks in the cement are absent (left).
compressive stresses can balance the external force. The compressive stresses are directed perpendicular to the interface. Hence, for a stem with no surface roughness, the axial component of the interface compressive stresses is relatively small [Fig. 9(A)]. In this case the axial load is transferred in an ineffective way, which requires high compressive stresses at the interface and results in high stresses in the cement. However, due to the absence of asperities, no local stress peaks are generated and the actual Von Mises stress peaks remain relatively low. When the surface roughness is increased, the load transfer is still not very effective because the main orientation of the compressive stresses is perpendicular to the axial direction. In addition, local stress peaks are generated around the asperities of the surface, resulting in relatively high Von Mises peak stresses [Fig. 9(B)]. When the surface roughness is increased beyond a certain roughness (in this study, 15 μm), the axial component of the compressive stresses becomes more dominant, resulting in a more effective method of axial load transfer. The interface stresses are reduced and with them the Von Mises stresses in the cement mantle [Fig. 9(C)].

DISCUSSION

In this study the effects of prosthesis surface roughness on cement stresses were analyzed using global and local axisymmetric FE models. The stem considered in the analyses was axially loaded and had a straight tapered shape without any irregularities other than its surface roughness. These assumptions limit the results found in this study to prosthesis types that have similar features. Collars, ridges, or other surface profiles may inhibit prosthesis subsidence and will therefore behave differently than the type of stem considered in this study. The analyses did not include the constraining capacity of the bone around the cement mantle or the bone-cement interdigitation. In addition, a perfect cement mantle around the stems was assumed, although it is known that rough surfaces may lead to a higher cement porosity in the vicinity of the interface due to air entrapment during insertion. These voids will lead to stress intensities and a higher probability of cement failure.

The macroscopic effect of surface roughness on interface friction was determined using a 2-D local FE model. The surfaces were assumed to have a perfect sinusoidal profile, few asperities, no microroughness and no adhesive properties. These assumptions explain the relatively low values determined for the coefficients of friction. Hampton and Mann et al. measured a coefficient of friction of about 0.2 between polished stainless steel and polymethylmethacrylate cement. The present study indicates that this amount of friction is generated with a prosthesis surface roughness of about 8 μm, which is by no means polished. Hence, the interpretation of the results presented in this study should be based on the general trends and mechanisms rather than on absolute values.

The results of the present study showed that stem-cement friction can be elevated by increasing the prosthesis surface roughness. Friction and cement stresses were not only affected by the value of the surface roughness, but also by the morphology of the roughness profile. This indicates that, although the roughness value of two components may be equal, their mechanical behavior may be different, which is important to realize when interpreting the possible effects of prosthesis surface treatments.

Surface roughness reduced prosthetic subsidence, the micromotions occurring at the interface, and global cement stresses. This was also found in earlier FE studies. Hence, it can be expected that stems generating higher interface friction induce less damage to the cement mantle as compared to low friction ones. In a laboratory experiment of a taper pushed into a cement mantle, we indeed found that rough stems showed less subsidence as compared to polished ones. However, cement damage was not reduced but increased with surface roughness. This finding was not found in the global FE analyses but could be explained by the local stress analyses, which showed local stress concentrations around the asperities of the surface roughness profiles. These local stress intensities can initiate cement cracks that may propagate to gross cement failure. Increasing the surface roughness beyond a certain value led to a change of load transfer. The component did not behave as a smooth stem anymore but as one with macroscopic surface ridges, thereby reducing the peak cement stresses. The exact value of the surface roughness that produces maximal cement damage will probably depend on many factors such as loading mode, prosthetic shape, geometry, and quality of the femoral bone and cement mantle, which make it impossible to formulate quantitative specifications for optimal prosthesis surface treatment based on this study.

The use of rough surfaces has been advocated because they would enhance the bonding strength of the stem–cement interfacial bond. However, there is no proof that these stems do not debond from their cement mantle after long-term clinical conditions. If they do debond, they may abrade the cement mantle, thereby producing cement wear particles. These particles may be transported to the endosteal bone surface where they can induce osteolysis. Based on the results presented in this article, these debonded stems should either be highly polished or have a macrotexture that prevents micromotions. Mat surfaced stems may be considered as a compromise between those
two options. They have improved bonding strength relative to polished ones and do not abrade the cement mantle as drastically as rough stems would do after debonding. However, there is substantial evidence that the bonding strength provided by these surfaces is inadequate to maintain the bond between the stem and the cement mantle.3,13–15 After debonding they will produce more wear particles as compared to polished stems, resulting in an acceleration of the failure process. This may also explain the higher clinical failure rate of the mat Exeter stem relative to the polished one.1 For these reasons, a stem with a mat surface may be regarded as a bad compromise.

Cement abrasion is caused by localized stresses in combination with micromotion. From this study it can be concluded that to minimize cement abrasion, debonded stems should either have a polished microstructure to minimize the local cement stresses or have a profiled macrostructure to minimize micromotions at the stem–cement interface.

References