On Evaluating the Implant Interface Bonding Strength

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Abstract
Three groups of CoCr alloy stem-acrylic bone cement interface specimens with different surface finishes were used, namely, satin finish (n = 10), grit blasting (n = 12), and plasma spray (n = 9) to determine the effects of surface roughness \( R_a \) of stem on early microcrack activities in cemented THA. The goals of the study were to evaluate microcrack activities due to roughening stem surface. The results of this study suggest that microdamage to the stem-cement interface occurs at 0.108 ± 0.031, 0.273 ± 0.034, and 0.300 ± 0.085 MPa for the three aforementioned interface groups, respectively, much lower than would be anticipated for normal activities in a traditional joint replacement. The acoustic signatures of failure of the interface was dependent on the interface morphology with rougher interfaces resulting in much greater microcrack intensity, but generally of lower magnitude when compared to the smooth satin finished interface. This suggests that the failure mechanism is different for rough versus smooth interfaces, which is also apparent by analysis of the fractured interface surfaces.

Introduction
The stem-cement interface is considered as a primary site leading to eventual clinical loosening of cemented total joint replacements. Many potential influencing factors such as extant porosity and gaps at the stem-cement interface,\textsuperscript{1-6} controlling the polymerization front of the curing cement,\textsuperscript{3,7,8} cement viscosity,\textsuperscript{9} and stem surface roughness and coating.\textsuperscript{3,10-13} Of these factors, surface roughness has the greatest influential effect on the
mating strength of stem-cement interface. However, the debate remains of whether to roughen, semi-roughen or not roughens the stem surface. For instance, it was reported that a roughened stem surface showed poor outcomes,14-17 while others reported that there was no significant difference between roughened and smooth (polished or satin) stem surfaces.18,19

The objectives of this study are: (1) to characterize microcrack activities at the stem-cement interface; (2) to correlate microcrack activity characteristics with classical mechanical measurements; and (3) to provide a means that can be used to predict mechanical behavior of the stem-cement interface. To accomplish these objectives, an acoustic emission technique (AE) was used that is capable of measuring the initiation, distribution, and accumulation of microcrack activities and associated energy in the loading process without the knowledge of the state of stress.20-22

Methods
Thirty-one stem-cement interface sandwich specimens were prepared for this study. Of these, twelve had a grit blasted finish (Ra=3.9 µm), ten had a satin finish (Ra=0.85 µm), and nine had a plasma sprayed finish (Ra=9.29). The final finished size of the stem bars was 5.9 x 11.1 x 125 mm. The surface treatments of these bars were glass bead blasting (satin finish), alumina grit blasting (grit blasted), or CoCr plasma spray (plasma sprayed). T The surface roughness of the stem, Ra, were measured using a contact profilometer (Surfcom 1800D, Zeiss) with a travel and cutoff length of 15 mm length of 5 mm, respectively. The PMMA bone cement (VersaBond™, Smith & Nephew Inc., Memphis, TN) were mixed for 40 – 50 sec and introduced to a rectangular mold over the CoCr alloy bars in a medium viscosity state. Specimens were allowed to cure for over 48 h in the mold before released. The edges were sanded to remove any excess cement. The prepared specimens were subject to shear strength tests under the regime shown in Fig.1 in which the cement bar was clamed on both narrow sides with the bottom end supported. A quasi-static loading (Instron 4465) was applied to the top surface of the stem bar at a crosshead rate of 1 mm / min. Each shear strength test was monitored using an acoustic emission system (ASMY-5, Vallen-Systeme GmbH, Germany). The AE sensors (Physical Acoustics, Inc., Princeton, NJ) have resonant and operating frequencies of 140 kHz, and 125 to 750 kHz, respectively. Five sensors were attached to the specimen surfaces with glue applied around their peripheries and silicon grease applied centrally for proper signal conductivity (Fig.1). The AE signals were conditioned first by preamplifiers (AEP4, 40 dB, Vallen-Systeme GmbH, Germany), and then fed to the AE system. All the post-test AE data were processed by an in house developed program (MapCrack©, at the Medical Acoustic Research Lab, the University of Memphis).
In this work, we categorize the standard quasi-static load in the following specified stages: 1) preyield - when the applied load is below yielding level, and 2) yield - when the applied load is between yield and slightly after the ultimate load.

Results
Measurements of surface roughness, $R_a$, apparent interface shear strength, microcrack activity onset stress, and the stress ratio were tabulated in Table 1.

Table 1. Surface roughness, apparent shears strength, microcrack activity onset stress, and stress ratio.

<table>
<thead>
<tr>
<th>Surface finish</th>
<th>Roughness $R_a$, $\mu$m</th>
<th>Shear strength, MPa</th>
<th>Onset stress, MPa</th>
<th>Stress ratio (onset/max), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satin finished</td>
<td>0.85 ± 0.03</td>
<td>0.377 ± 0.056</td>
<td>0.108 ± 0.031</td>
<td>25.842 ± 6.229</td>
</tr>
<tr>
<td>Grit blasted</td>
<td>3.95 ± 0.15</td>
<td>1.915 ± 0.107</td>
<td>0.273 ± 0.034</td>
<td>15.200 ± 2.335</td>
</tr>
<tr>
<td>Plasma sprayed</td>
<td>9.29 ± 0.29</td>
<td>9.480 ± 0.317</td>
<td>0.300 ± 0.085</td>
<td>3.237 ± 0.882</td>
</tr>
</tbody>
</table>

The accumulative microcrack activities in the three loading stage are summarized in Tab.2. Statistical tests showed that there are significant differences of microcrack intensity between the smooth and roughened interfaces in the preyield loading stage. When examining the quantity of microcrack activities in the preyield stage relative to the microcrack activities in preyield and yield stages, the ratios are 51%, 32%, and 27% in the plasma sprayed, grit blasted, and satin finished surfaces, respectively (Tab.2).
Table 2. Microcrack activities, intensities, and average microcrack energy in the preyield and yield loading stages, and preyield activities to preyield and yield activities ratios.

<table>
<thead>
<tr>
<th>Surface finish</th>
<th>Microcracks</th>
<th>Preyield stage</th>
<th>Yield stage</th>
<th>Ratio of preyield to preyield + yield stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satin finish</td>
<td># of activities</td>
<td>642 ± 304</td>
<td>1036 ± 310</td>
<td>27.42 ± 5.80</td>
</tr>
<tr>
<td></td>
<td>Activity intensity, #/mm²</td>
<td>0.999 ± 0.426</td>
<td>1.810 ± 0.541</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Average activity energy, eu</td>
<td>112.799 ± 36.171</td>
<td>323.336 ± 74.397</td>
<td>---</td>
</tr>
<tr>
<td>Grit blasted</td>
<td># of activities</td>
<td>1519 ± 397</td>
<td>2624 ± 235</td>
<td>31.87 ± 6.20</td>
</tr>
<tr>
<td></td>
<td>Activity intensity, #/mm²</td>
<td>3.197 ± 0.727</td>
<td>4.587 ± 0.411</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Average activity energy, eu</td>
<td>8.424 ± 1.131</td>
<td>69.207 ± 18.421</td>
<td>---</td>
</tr>
<tr>
<td>Plasma sprayed</td>
<td># of activities</td>
<td>5436 ± 930</td>
<td>5028 ± 581</td>
<td>50.64 ± 4.31</td>
</tr>
<tr>
<td></td>
<td>Activity intensity, #/mm²</td>
<td>15.650 ± 2.818</td>
<td>13.909 ± 1.760</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Average activity energy, eu</td>
<td>7.914 ± 1.458</td>
<td>127.805 ± 30.632</td>
<td>---</td>
</tr>
</tbody>
</table>

ESEM observations of the stem and the corresponding mating cement surfaces indicate that there is a clear distinction between the amount of breakage of cement fragments in the stem surfaces (indicated by the dark areas in Fig.2). There is only one dark area found in satin finished specimen (Fig.2a). The cross section observations did not show any substantial microcracks that appeared to be due to the shear rapture.

![Figure 2. Post-test stem surface morphology. The light and dark areas are the metal and the broken interlocked cement, respectively, (a: satin finish, b: grit blasted, and c: plasma sprayed).](image)

**Conclusion**

This work investigated microcrack activities at the clinically significant femur stem and cement interface. It was found that:

- Microcrack activities could onset at a surprisingly low stress level, 0.108 ± 0.031, 0.273 ± 0.034, and 0.300 ± 0.085 MPa for the satin finished, grit blasted, and plasma sprayed interface groups, which are much lower than previously thought.
- There were significantly greater microcrack intensity in the roughened stem interface than that in the satin interface.
The average microcrack activity energy was significantly greater in the satin finished interface than that in the roughened interfaces, which indicated the failure mechanism in the satin finished interface is the "true interface debonding," whereas the roughened interfaces are dominated by the breakages of interlocked cement fragments.

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References


