Corrosion Behavior of Ti-6Al-4V Orthopaedic Alloy Under Tensile Stress

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Statement of Purpose: Surfaces of Ti-6Al-4V orthopaedic devices experience a range of tensile stress magnitudes in vivo, such as in the case of hip and knee stems with off-axis loading, bone screws, and the lateral faces of fracture fixation devices. Recent retrieval studies suggest that high stress regions on these devices experience more localized corrosion, even in the absence of any corrosion cracks [1,2]. While the effects of crevice conditions, fretting, fatigue, and other mechanically-assisted forms of corrosion have been investigated for orthopaedic metals [3], the effects of pure tensile stress on corrosion behavior remain undocumented. Since tensile stress has a demonstrated effect on the corrosion rate and passivation behavior of stainless steels [4] and NiTi alloys [5], it follows that similar effects may occur with titanium alloys. The purpose of this study is to compare the corrosion rate and passivation behavior of Ti-6Al-4V under varied physiologically-relevant tensile stresses.

Methods: Sheets of Ti-6Al-4V alloy (McMaster-Carr) was acquired and machined into thin strips (152.4 mm x 25.4 mm x 0.38 mm). U-Bend stress corrosion testing specimens using two-point loading conditions (Figure 1) detailed in ISO 7539-2 were designed such that the apexes of the bent strips (9 total) experienced 0% (control), 50%, and 100% of the yield stress (σ_y) of Ti-6Al-4V. The tensile stress face at the apex was exposed to the electrolyte (1X phosphate buffered saline, pH 7.4) as the working electrode, while the remainder of the each strip was electrically isolated using 2-part epoxy. The 3-electrode cell (including graphite counter-electrode, saturated calomel reference-electrode (SCE)) was connected to a Gamry Interface 1000 potentiostat to measure electrochemical behavior. Polarization resistance R_p, inversely related to corrosion rate (current density i_{corr}) by the relation $i_{corr} = 2.303*[\beta_a\beta_c/(\beta_a+\beta_c)]*R_p^{-1}$, was monitored by potentiodynamic linear polarization (LPR) testing and potentiostatic electrochemical impedance spectroscopy (EIS) with data fit to a Randles equivalent circuit. Cyclic polarization (CP) was performed to determine the corrosion rate, anodic/cathodic Tafel constants β_a and β_c, and passive corrosion rate. Specimens were assessed microscopically after electrochemical testing using non-contact profilometry.

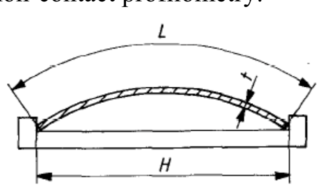

Figure 1. Two-point loading conditions (ISO 7539-2):
$L = (ktE/\sigma_{apex}) \sin^{-1} (H\sigma_{apex}/ktE)$

Results: The active corrosion rate increased for stressed Ti-6Al-4V specimens, with a > 400% increase in i_{corr} from control at 50% σ_y (Figure 2). Trends in corrosion rates calculated from LPR, EIS (fit to Randles circuit, solution resistance R_s in series with R_p and constant phase element CPE in parallel), and CP were similar. The passive corrosion rate at E = 1 V vs. SCE also increased from 12.4 ± 8.7 µA/cm^2 (control) to 372.0 ± 194.6 µA/cm^2 (50% σ_y) and 62.0 ± 28.2 µA/cm^2 (100% σ_y). Upon microscopic examination directly after polarization, Ti-6Al-4V specimens experiencing 50% σ_y demonstrated a higher surface density of pits (Figure 3). Corrosion pits on the 50% yield stress specimens were deeper (4-5 µm) than pits on corroded control specimens (1-1.5 µm).

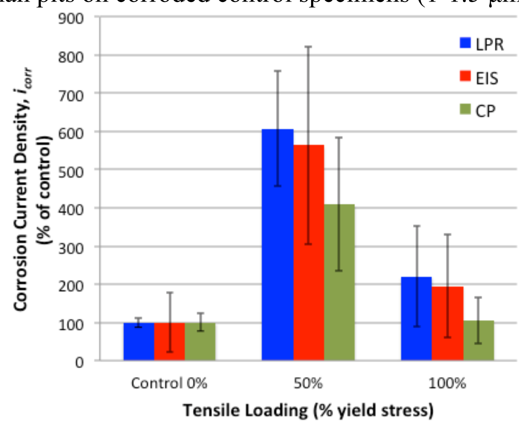

Figure 2. Corrosion rate measured by 3 techniques for varied tensile stresses. Control i_{corr} values were 24.2, 34.9, and 16.6 nA/cm^2 for LPR, EIS, and CP, respectively.

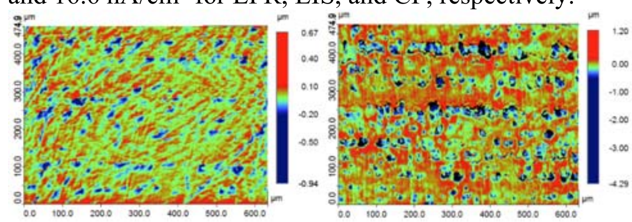

Figure 3. Deeper and more numerous corrosion pits (dark blue regions) noted in profilometric scan of Ti-6Al-4V under 50% σ_y tension (right) than control (left).

Conclusions: These preliminary in vitro findings suggest that tensile stresses contribute to higher corrosion rates and more pronounces pitting for this material compared to unstressed controls of the same material. An applied tensile stress of 50% σ_y resulted in higher active and passive corrosion rates and more severe pitting corrosion for Ti-6Al-4V compared to the unstressed material. An applied tensile stress of 100% σ_y had a less pronounced effect, possibly due to microstructural changes from mild plastic deformation. These findings would affect the interpretation of other in vitro and retrieval corrosion studies. Microstructural investigation of the materials exposed to the different stress conditions is ongoing. The corrosion behavior of intermediate stress states (25% σ_y, 75% σ_y, 125% σ_y) is currently being investigated.

References: [1] Lanting BA. J Arthrop. 2014; *In Press*. [2] Harman MK. J Biomed Mater Res. 2011;99:431-439. [3] Jacobs JJ. J Bone Joint Surg. 1998;80-A:268-282. [3] Bundy KJ. J Biomed Mater Res A. 1986;20:493-505. [5] Liu IH. J Dent Res. 2007;86:539-543.