Laser Textured Ca-P Bioceramic Coatings for Hard Tissue Replacement

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INTRODUCTION

Def: Biomaterials are synthetic or natural materials intended to function appropriately in a bio environment and thereby restore the function of a damaged or diseased tissue.
Three important factors that dictate the success of a biomaterial are:

• **Type of Material**: metals, ceramics, polymers, and natural materials.

• **Design**: appropriate mechanical properties, durability, functionality, and biological response.

• **Biocompatibility**: Acceptance of the biomaterial by the surrounding tissues.
Hierarchical organization of bone

- Human bone is a hierarchical organization at different length scales.
- Understanding the structure-property relationship of this hard tissue is important towards effective design of load bearing implants.

Sequential bioreaction at the implant surface

- Protein adsorption
- Cells interaction
- Cell orientation and contact guidance.
- Organization and multiplication into complex tissues.
Ca-P based coating on Ti-6Al-4V using a Nd:YAG laser

- Precursor Material: Ca$_5$(OH)(PO$_4$)$_3$ powder.
- Substrate: Ti-6Al-4V

**Laser parameters used for the coating:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Stand off distance</td>
<td>356 mm</td>
</tr>
<tr>
<td>Spot size</td>
<td>400 µm</td>
</tr>
<tr>
<td>Scan speed</td>
<td>500 mm/sec</td>
</tr>
<tr>
<td>Avg. power</td>
<td>215 W, 300 W</td>
</tr>
<tr>
<td>Hatch distance</td>
<td>0.1 mm, 0.2 mm</td>
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*Fig. Schematic of the continuous wave Nd:YAG laser system used for the coating process*
Microstructure and Morphological evolutions

- Textured Ca-P coatings resulting from the varying laser input power and track overlap.
- Decrease in Ca and P atomic concentration with increasing laser power.

Fig. SEM and the corresponding EDS spectra as inset for the samples processed at (a) 215 W 0.1 mm hatching, (b) 300 W 0.1 mm hatching, (c) 215 W 0.2 mm hatching and (d) 300 W, 0.2 mm hatching.
**Phases within the coatings:** CaTiO$_3$, TiO$_2$, Ti, Al, Al(OH)$_3$, Al$_2$O$_3$, VO(OH) and Ca$_5$(OH)(PO$_4$)$_3$.  

*Fig. 4 XRD for the samples processed at (a) 215 W 0.1 mm hatching, (b) 215 W 0.2 mm hatching, (c) 300 W 0.1 mm hatching and (d) 300 W, 0.2 mm hatching.*

*Fig. SEM of the cross-section of the samples processed at 215 W 0.2 mm hatching.*

- Textured Coating
- Encapsulated Ca-P phases
- Metallurgical bonding at the interface
Fig. Variation of surface roughness parameters as a function of laser processing parameters.

- Maximum surface roughness for the sample processed at a laser power of 215 W and 0.2 mm hatching.
- Controlled and regular topographic cues.

Fig. 7 Confocal 3-D surface images of the laser processed samples.
• Improved bioactivity for the sample processed at a laser power of 215W and 0.1mm hatching
Fig. SEM micrographs revealing the formation of globular apatite like layer following immersion in SBF for different time periods.

- Transition from a globular to segregated apatite phase with increasing immersion time.

Fig. Dependence of Ca and P atomic concentrations and Ca/P atomic ratio to SBF immersion time for the samples processed at 215 W 0.1 mm hatching.

- Ca/P atomic ratio reached the atomic ratio of (HA) only after 96 hours of immersion period.
Mechanism of apatite formation

- Precipitation of OH\(^-\) ions on the textured surface due to beneficial phases such as CaTiO\(_3\) and TiO\(_2\).

\[
\text{CaTiO}_3 + 3\text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{Ti(OH)}_4
\]

\[
\text{TiO}_2 + 2\text{H}_2\text{O} \rightarrow \text{Ti(OH)}_4
\]

- Presence of a negatively charged surface enhanced the formation of apatite.

\[
10\text{Ca(OH)}_2 + \text{H}_3\text{PO}_4 \rightarrow \text{Ca}_{10} (\text{PO}_4)_6(\text{OH})_2 + 18 \text{H}_2\text{O}
\]
Biocompatibility

**Test:** In-vitro culture of the mouse MC3T3-E1 osteoblast cells.

- Improved cell viability on the laser processed samples as compared to the control (WST-1 assay).
- Improved cell adhesion of the laser processed samples were characterized by the anchoring of the lamellipodia to the textured grooves.

Fig. 11 (a) WST-1 assay and SEM morphology of the MC3T3-E1 osteoblast cells after 1 day incubation on (b) control and the samples laser processed at (c) 215 W 0.1mm hatching, (d) 300 W 0.1 mm hatching, (e) 215 W 0.2 mm hatching and (f) 300 W, 0.2 mm hatching.
Fig. Cytoskeleton assessment of MC3T3-E1 osteoblasts after 1 day culture on (a) control and the samples laser processed at (b) 215 W 0.1 mm hatching, (c) 300 W 0.1 mm hatching, (d) 215 W 0.2 mm hatching and (e) 300 W, 0.2 mm hatching.

- Well developed network of focal adhesion contacts for the laser processed samples.
- Enhanced spreading on the textured surfaces as compared to the control.
- More stressed actin filaments on the textured surfaces.
CONCLUSIONS

• A novel laser induced direct melting technique is established to synthesize physically textured Ca-P coatings on Ti-6Al-4V.

• XRD studies of the coated sample showed the presence of beneficial biocompatible phases such as CaTiO$_3$ and TiO$_2$ within the coatings.

• Improved bioactivity of the coated samples were proved by the formation of an apatite like phase following immersion in SBF.

• Rapid saturation of Ca/P atomic ratio to the atomic ratio of HA (1.67) was observed with increase in SBF soaking time.

• Biocompatibility of the coated samples were proved with respect to enhanced cell proliferation and spreading on the laser textured surfaces.
ACKNOWLEDGEMENTS:

• The authors would like to acknowledge Center for Laser Applications (CLA) University of Tennessee Space Institute for supporting this work.
THANK YOU