ABSTRACT
The aim of this study is the evaluation of mechanical and biomedical characteristics of commercially pure F67 grade 2 titanium sheets and its application in cranial implants. Through tensile tests, it was shown that the material has good ductility, a important characteristic that allows the implant manufacturing by incremental sheet forming.

KEY WORDS
Titanium, Cranial Implants, Biomechanical Characteristics, Incremental Sheet Forming

1. Introduction
Bone loss of skull may occur due to tumors, infections and mainly fractures, which typically occur in automobile accidents and interpersonal acts. When the affected area exceeds 100cm², it becomes necessary to use implants because the bone layer loses its ability to regeneration and reintegration. Most implants (91.2%) are located in regions neurocranial and temporal areas corresponding to 'A' and 'B' of Figure 1d [1].

Titanium and its alloys have been widely used in the manufacture of cranial, maxilo, facial and dental implants, due to its excellent mechanical properties, such as low elastic modulus (relative to steel, but still 4 to 5 times higer than human bone), corrosion resistance and biocompatibility [2].

2. Characteristics of CP Titanium F67 grade 2
2.1 Phisico-chemical characteristics
Some properties phisico-chemical of the commercially pure titanium F67 grade (99.1% of Ti) are show listed in table 1:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>4.51 g/cm³</td>
</tr>
<tr>
<td>Atomic number</td>
<td>22</td>
</tr>
<tr>
<td>Atomic mass</td>
<td>47.90u</td>
</tr>
<tr>
<td>Fusion point</td>
<td>1648C à 1704C</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>high</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>116 GPa</td>
</tr>
<tr>
<td>Elongament (%)</td>
<td>40</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.34</td>
</tr>
<tr>
<td>Hardening</td>
<td>BHN 190 (~192 Vickers)</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>1.5 a 2.5 m/Ω mm²</td>
</tr>
<tr>
<td>Yeld stress</td>
<td>350-700 N/mm²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>Fe(%)</th>
<th>C(%)</th>
<th>N(%)</th>
<th>H(%)</th>
<th>O(%)</th>
<th>Others(%)</th>
<th>Ti(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.20</td>
<td>0.08</td>
<td>0.03</td>
<td>0.015</td>
<td>0.18</td>
<td>0.4</td>
<td>99.1</td>
</tr>
</tbody>
</table>

ASTM-F67 and 2 ASTM-F136 grade titanium classes has specific applications for the biomedical area. They are manufactured with high quality control, since it is temporary or permanent components to be incorporated into the human body [3].
2.2 Biomechanical characteristics

Besides the physical, chemical and mechanical properties of titanium, this metal has specific characteristics related to the biomechanics area, as shown below [3]:

a) It is resistant to corrosion and reactive, due to the fast formation of an oxide layer on the surface when in contact with body tissues;
b) It has an appropriate density for use as a prosthesis (4.45 g/cm³);
c) It is biocompatible; its presence in the body does not cause rejection (swelling or inflammation) at the implant site or in the biological system (allergies);
d) It is biofunctional: it meets both the aesthetic and practical functions (statics and dynamics), due to its dimensional stability;
e) It is bioinert; there is not formation of fibrous encapsulation around the implant. The material does not release any type of component or in minimal quantity;
g) It is sterilizable;
h) It has good formability, fitting the complex geometry of conformation (cranial implants).

2.3 Microstructural characteristics

The commercially pure titanium (Ti-CP) sheets, at room temperature, shows hexagonal compact crystal structure [4]. This configuration, in a first look, is a low ductility indicator. In this case, the incremental sheet forming (described in the chapter 3), besides allowing the production of unique and complex pieces, will also used to increase the sheet formability [5].

Even with respect to microstructure, the material, in \( \alpha \) phase, reveals an elongated grain boundary, as shows in the Figure 2:

![Figure 2. Optical micrography of CP titanium surface [6]](image)

2.4 Stress-strain curve

The stress-strain curve is obtained through tensile test, according to DIN EM 10002 standard. Were removed two samples of Ti-CP F67 grade 2, 0.5mm thick, with the direction of lamination of 0 and 90° in relation to the length of the specimen. Figure 4 shows the engineering stress-strain curves obtained.

During the lamination process of sheet metal, the deformation of the microstructure occurs and if the original grains were elongated in the lamination direction (Figure 3). This stretching causes the sheet has a greater ability to deform without fracture.

![Figure 3. Effect of lamination process on the microstructure of material](image)

The longitudinal stress-strain curve (Figure 4) presents a major engineering strain of the transverse stress-strain curve. Thus, for a 3D elliptical geometry, for example (similar to the shape of a skull), the ideal way of forming would position the axis of the ellipse parallel to the direction of rolling. The larger deformation would occur in the same direction as the lamination, where the material is more ductile, decreasing the chances of fracture of the plate.

![Figure 4. Stress-strain curves of Ti-CP F67 grade2, according to lamination direction.](image)
After tensile test, it was discovery that the Ti-CP sheet showed a ductile fracture, characterized by a necking visible and the rupture angle of about 45° (Figure 5) [7].

![Figure 5. Ductile fracture of titanium sheet](image)

Through tensile test, can be obtained the engineering strain, elongation, ultimate engineering stress and flow curve.

\[ \varepsilon = \left( \frac{l-l_0}{l_0} \right) \]

\[ \varepsilon = \left( \frac{110.9-80}{80} \right) \]

\[ \varepsilon = 0.38 \]

\[ \delta = l-l_0 \]

\[ \delta = 30.9 \text{ mm} \]

\[ \sigma_u = \frac{F_{\text{max}}}{A_0} \]

\[ \sigma_u = \frac{4947.7}{10.5} \]

\[ \sigma_u = 471 \text{ MPa} \]

\*\( A_0 \) is the cross-sectional area of the tensile test units.

### 2.5 Stress flow curve \((k_f \times \varphi)\)

The flow curves, which they are always obtained experimentally can be described by a mathematical function. In general, to cold deformation, this equation has the following form [8]:

\[ k_f = C \varphi^n \]

- ‘C’ is a material constant, to \( \varphi = 1 \)

Other data necessary for determining stress flow curve are [9]:

- Engineering strain \( (\varepsilon) = 0.25 \), according to Figure 4;
- True strain \( (\varphi) \), relative to ultimate stress moment \( (\sigma_u) \) is:
  \[ \varphi = \ln(1 + \varepsilon) \]
  \[ \varphi = \ln(1 + 0.25) \]
  \[ \varphi = 0.096 \]

The true stress \((k_f)\), corresponding to ultimate engineering stress \((\sigma_u)\) can be obtained by:

\[ k_f = \sigma_u (1 + \varepsilon) \]

\[ k_f = 471(1 + 0.25) = 589 \text{ MPa} \]

In the ultimate stress moment, the true strain \((\varphi)\) is equal to hardening rate \((n)\):

\[ \varphi = n \]

\[ n = 0.096 \]

With \( k_f \varphi_u \) value, ‘C’ constant is obtained:

\[ k_f \varphi_u = C \varphi^n \]

\[ 589 = C \cdot 0.096^{0.096} \]

\[ C = 737.6 \text{ MPa} \]

Finally, the Ti-CP F67 grade 2 flow curve \((k_f \times \varphi)\) can be mathematically designated by:

\[ k_f = 737.6 \varphi^{0.096} \]

![Flow stress curve of CP Titanium grade 2](image)
Converting the stress flow curve in logarithmic scale, can be obtained the material hardening rate \((n)\). Usually, the result is a straight and \(n\) value is indicated by its slope \((n = \text{tg}\alpha)\). The logarithmic plot and \(n\) value its shows in Figure 7.

![Log-log flow stress curve of CP Titanium grade 2](Image)

Figure 7. Stress flow curve, in log-log axis

\[
\begin{align*}
n & = \text{tg}\alpha \\
n & = \text{tg}14.17 \\
n & = 0.25
\end{align*}
\]

The hardening rate indicates the material resistance to plastic deformation. As a comparison, aluminum has an rate of 0.13. It is, therefore, much more ductile than titanium, although it is not biocompatible.

Following Table 2 shows the obtained values through tensile test:

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yeld stress</td>
<td>(\sigma_E)</td>
<td>350 MPa</td>
</tr>
<tr>
<td>Elongation</td>
<td>(\delta)</td>
<td>38%</td>
</tr>
<tr>
<td>Ultimate stress</td>
<td>(\sigma_u)</td>
<td>471 MPa</td>
</tr>
<tr>
<td>Engineering strain at the moment of ultimate stress</td>
<td>(\varepsilon)</td>
<td>0.25</td>
</tr>
<tr>
<td>True strain at the moment of ultimate stress</td>
<td>(\varphi)</td>
<td>0.096</td>
</tr>
<tr>
<td>Hardening rate</td>
<td>(n)</td>
<td>0.25</td>
</tr>
<tr>
<td>True stress corresponding to the ultimate engineering stress</td>
<td>(k_f)</td>
<td>589 MPa</td>
</tr>
</tbody>
</table>

| Ti-CP F67 grade 2 flow curve expression | \(k_f = 737,6\varphi^{0.096}\) |

3. Application of Ti-CP F67 grade 2 in cranial implants

After knowing the mechanical properties of titanium, was made a implant model, corresponding to the top region of a skull. We used a mechanical forming process, called Incremental Sheet Forming (ISF), allowing the use of conventional CNC equipment and tooling simple. For forming, can be used specific equipment or an adapted 3 axis CNC machining center.

In the incremental sheet forming, a simple tool of generic profile, produces a localized plastic deformation in a sheet region. This region changes according to tool movement. [10]. Thus, the deformation occurs gradually, increasing the sheet conformity, when compared with the conventional forming process [11]. The Figure 8 shows the fixed sheet being deformed by a semi-spherical tool.

![Schematic representation of the incremental sheet forming](Image)

Figure 8. Schematic representation of the incremental sheet forming (Martins, et al. 2008)

It is a low costs process, since a simple tool can be used for the manufacture of a variety of irregular and asymmetric shapes (highly customized medical products, e. g.)[12].

3.1 Implant development

Using computed tomography (CT) imagens of a healthy skull, a CAD model was created (only the top region, simulating a trauma in this area). Following was used a CAM software to determine the manner as the tool move itself on the sheet. The toolpath was converted in ‘G’ codes and sent to 3 axis machine center, where it was performed the sheet forming. The Table 3 and Figure 9 show the steps for making the implant prototype.

<table>
<thead>
<tr>
<th>No.</th>
<th>Step</th>
<th>Resource</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acquisition of JPG pictures (112 skull sections)</td>
<td>Computed tomography (CT)</td>
</tr>
<tr>
<td>2</td>
<td>Geration of 3D File</td>
<td>Free software</td>
</tr>
</tbody>
</table>
### 4. Conclusion

The knowledge of the titanium properties is essential to determine the manufacturing parameters of cranial implants through incremental sheet forming. Despite of present a hexagonal compact crystal structure, commercially pure titanium showed good ductility.

The force required to deform the sheet is proportional to hardening rate. The Ti-CP F67 grade 2 showed a lower hardening rate (0.25), therefore is suitable for sheet forming process.

The incremental sheet forming process is appropriate for the implants manufacture, since it has low costs and customization capabilities.

### Acknowledgements

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### References


