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SURFACE ANALYSIS OF A TITANIUM PLATE IMPLANT USED FOR HUMERUS FRACTURE AFTER MECHANICAL TESTING

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Abstract: *In clinical practice, proximal humeral fractures are a frequent fracture type. The purpose of this study was to test mechanically and evaluate the surface properties for an anodized titanium bone plate by simulating an assembly that reproduces the fracture fixation of a humeral defect. The experimental assembly was comprised of an artificial bone in which a defect was created by removing a bone region. The defect was remediated using a bone plate. The assembly was tested in compression in order to analyze the mechanical behavior. During compression testing, the bone plate was stressed in bending, the anodized layer on the surface failed and the stressed regions became obvious. The roughness and wettability of the bone plate surface was tested prior and post mechanical testing. We found that the surface properties of the bone plate were modified after mechanical testing. This change in surface morphology plays an important role in the implant - tissue interaction, as surface wetting and surface free energy are greatly influenced by the mechanical forces that act on the implant after surgical procedure.*
Key words: *titanium, bone plate, compression testing, roughness, wettability, interaction.*

1. INTRODUCTION

In clinical practice, proximal humeral fractures are a frequent fracture type, making around 4%–5% of all fractures [1]. The incidence of proximal humeral fractures has steadily risen with population aging. Although surgery is still the recommended course of action for unstable fractures, the majority of proximal humeral fractures may be managed conservatively. Even with ongoing advancements in surgical methods and internal fixation materials, postoperative problems still occur at rates between 16% and 49% [2, 3]. The problems resulting from surgical revision owing to fixation loosening, as well as concomitant soft tissue abnormalities and infection, are very difficult to manage. Fractures of the distal humerus are regarded as difficult injuries. For effective outcomes, secure fixation with anatomical reduction is necessary; nonetheless, it has drawbacks, particularly when treating severely comminuted fractures [4]. While precise articular surface restoration is essential in the treatment of intra-articular fractures, repairing the metaphyseal segment – which serves as the support structure for articular fragments – is often just as crucial [5]. Therefore, in some circumstances, precise bone regeneration and overall success may depend on the fixation of tiny metaphyseal fragments [6, 7].

With a triangle structure that widens out from the humeral diaphysis, the distal humerus has a complicated morphology. The medial column, lateral column, and articular portion comprise the distal humerus and together they create the triangle's horizontal limb. The systematic reconstruction of distal humerus fractures is thought to benefit from this triangular idea. Achieving total build stability requires reconstructing both columns and the articular surface [8, 9].

Different surgical procedures, including as intramedullary nails, locking and nonlocking plates, tension band sutures, and prosthetic replacement, are advised for displaced proximal humeral fractures. Nowadays, locking plate fixing is seen to be the best option when it is

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possible [10]. The danger of wound infection, implant-related issues (such as screw cutting, screw loosening or plate impact), postoperative fracture nonunion, reduction loss, and humeral head necrosis are only a few of the many short- and long- term drawbacks that it still has [11,12].

The purpose of this study was to test mechanically and surface properties an INTERCUS GmbH bone plate model Abb. 750.591106 by simulating an assembly that reproduces the fracture fixation of a humeral defect.

2. MATERIALS AND METHODS

The experimental assembly was comprised of an artificial bone (SAWBONES model #3404) in which a defect was created by removing a region. The defect was remediated using a INTERCUS GmbH bone plate model Abb. 750.591106. Plate fixation was performed by a qualified surgeon, the resulting assembly was fixed in a base to provide rigid support for testing. The assembly is presented in fig. 1 in frontal and lateral view.

Fig. 1. The assembly used for mechanical testing.

The assembly was tested in compression using the universal testing machine Walter + Bai LFV 300 using a plane surface to rest the base of the assembly, while loading was induced on the region of maximum curvature of the bone. This loading pattern was considered to be the worst-case scenario by applying the load axially on a reduced surface area.

The load - displacement curves during the test were recorded and processed to observe the mechanical behavior and determine the rigidity of the assembly.

The stressed plate was removed and inspected using a digital microscope and roughness tests were performed on highly stressed regions using a Form Talysurf® i-Series PRO Range device from Taylor Hobson.

Surface wetting was studied via a KRUESS DSA 30 contact angle analyzer using 3 liquids, water, diiodomethane and ethylene glycol to determine the surface free energy. The studies were performed on the bone plate prior and post mechanical loading.

Throughout this work sample coding uses "unstressed" for all tests performed on prior and "stressed" for post loaded specimens.

3. RESULTS & DISCUSSION
3.1. Mechanical testing

The mechanical testing was performed in compression, in displacement control using a rate of 1mm/min and by applying the load on the region of maximum curvature of the epiphysis.

The load - displacement curve constructed with data recorded during the test is presented in fig. 2.

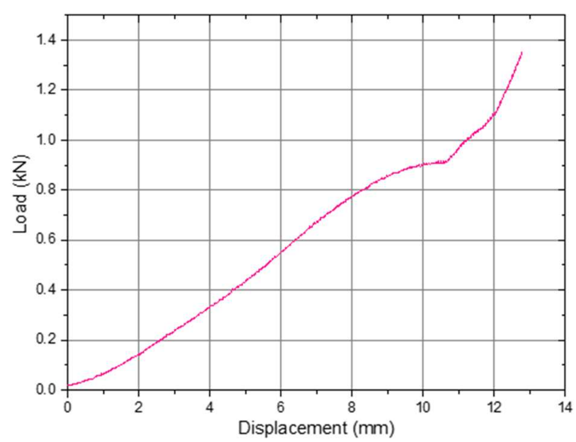
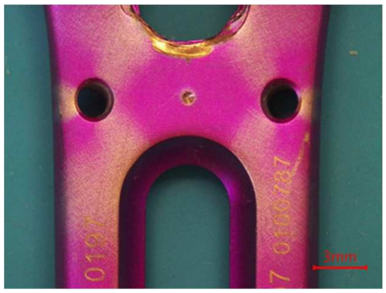


Fig. 2. Load - displacement curve for the tested assembly.

The load displacement curve is analyzed beyond 2mm displacement, since in the 0-2mm region the parts of the assembly are sliding and rotating to a position that generates a firm contact. The load and displacement vary linearly up to 386N followed by a change in slope reflecting a different load distribution within the assembly. The onset of permanent deformation is appreciated at 892N. The rigidity of the assembly was determined in the linear region of the curve and it was found to be 0.095kN/mm.



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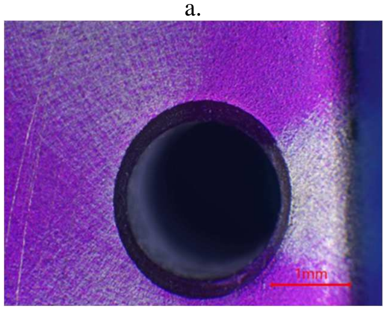

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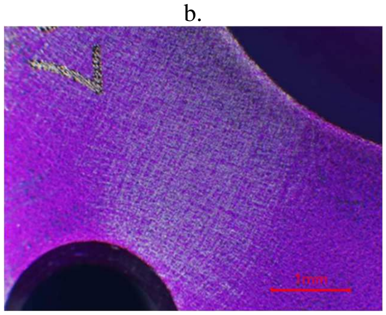

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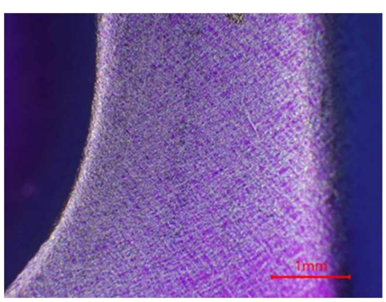


d.

Fig. 3. Stressed regions on the bone plate with a. general appearance, b. detail from region 1, c. detail from region 2 and c. detail from region 3 și d. region was more intensely stressed.

The ascending trend of the curve beyond 10mm displacement is caused by the contact between the epiphysis and diaphysis of the bone, point where failure of the assembly was considered.

Using a digital microscope detail on the stressed regions were captured and a selection is presented in Fig. 3. The aspects presented show that the bone plate was stressed in bending, the anodized layer on the surface failed and the stressed regions became obvious.

Given its position in the assembly the bone plate was stressed in bending and on the studied surface and on the surface depicted in Fig. 3.a the tensile component was present, easily observed by failure of the anodized layer. The pattern observed in Fig. 3.b. and c. reflect an uneven stress distribution spread between the screw and guiding holes, the failure pattern of the layer resembling a vector field plot. The detail presented in Fig. 3.d shows that in this region massive layer damage occurred, suggesting that this region was more intensely stressed than others, reason to direct the surface and wetting analysis on it.

3.2. Surface properties evaluation

3.2.1. Roughness

The roughness of the surface was tested on the plate prior and post mechanical testing. The regions of interest on the tested plate were the ones with obvious signs of surface modifications.

Five tests were performed on each type of surface, on an evaluation length of 8±1mm. Given the curved surface the workflow comprised a leveling by excluding the form factor and applying two Gaussian profile filters λs=2.5µm and λc=0.25mm. The same protocol was applied for all traces.

The amplitude parameters determined from the roughness profiles are the arithmetical mean deviation of the assessed profile (Ra), the root mean square deviation (Rq), the skewness (Rsk) and kurtosis (Rku), the maximum height of profile (Rz) and the total height of the profile (Rt).

The comparison of these parameters presented in Fig. 4 and 5 show a decrease in Rq, Rt, Rz and Ra values in case of the stressed regions, differences that were found statistically significant (ANOVA test with α=0.05).

The Rt parameter appears to be strongest influenced by surface morphology change post plastic deformation, Rz in a lesser extent, while the Rq and Ra parameters appear to be least influenced.

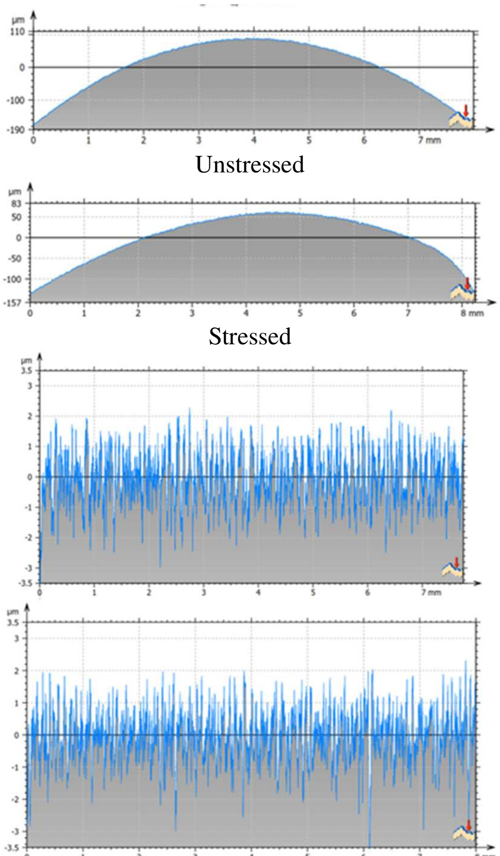


Fig. 4. A selection depicting the a. initial recording and b. roughness profile post processing.

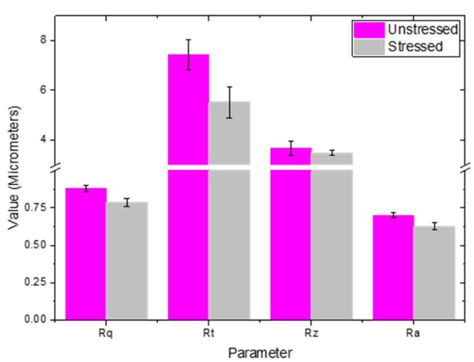


Fig. 5. Comparison of average roughness parameters Rq, Rt, Rz, Ra

An important aspect for the surface profile is given by the Rsk and Rku that reflect the height distribution. The decrease in absolute value of the skewness, as observed in Fig. 6, reflects that on the surface the distribution of peaks and valleys became more symmetrical, as material movement occurred during plastic deformation.

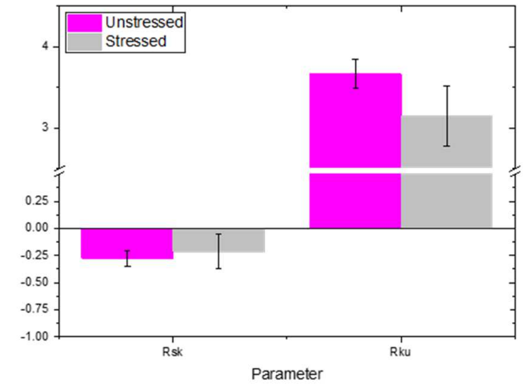


Fig. 6. Comparison between Rsk and Rku

The kurtosis decrease reflects a similar change, from a surface with high peaks and low valleys by plastic deformation a surface with lower peaks and valleys occurs.

This change in surface morphology plays an important role in the material - tissue interaction, as surface wetting and surface free energy are greatly influenced by this behavior.

3.2.2. Wettability

Surface wetting studies were performed on an unstressed and the stressed bone plate, for comparison.

Fig. 7. Sessile drop aspect

On the stressed plate the sessile drops were placed on the stressed regions presented earlier. A selection of images of the sessile drops for the three liquids used are presented in fig. 7.

The surface free energy was determined using the Fowkes method with couples of water - diiodomethane and diiodomethane - ethylene glycol. To simplify the notation, each liquid is symbolized by its capital letter i.e. W for water, D for diiodomethane and E for ethylene glycol.

The tests were performed 5 times for each liquid, the results were averaged and presented for comparison in fig.8.

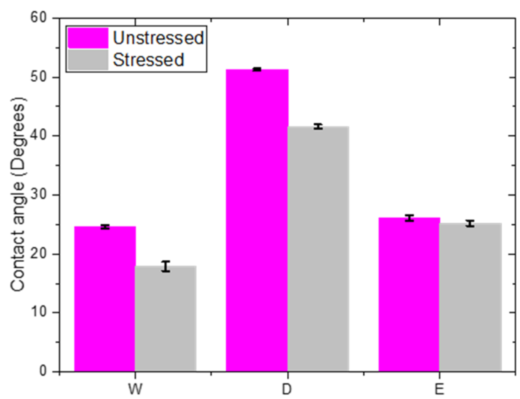


Fig. 8. Comparison of average contact angle values on the surface of the unstressed and stressed specimens

A noticeable difference appears between the average values of the contact angle for water and diiodomethane. On the stressed regions the average contact angle values decreases, suggesting an enhancement in surface wetting. When ethylene-glycol was used the change is very small, but still statistically significant as the results of the one way ANOVA test showed.

It was observed that on the stressed regions the surface wetting is enhanced, regardless of the liquid used. The surface free energy was determined and in fig. 9 a comparison chart is presented.

First a slight difference was observed between the resulting surface free energies using W-D and E-D, approximately of 0.5-1mN/m. The surface free energy (we report the one determined using the couple W-D) of the unstressed surface is 67.01±0.15mN/m, while on the stressed one it averages 70.43 ± 0.29mN/m. An increase of the surface free energy by 3.42mN/m was observed. Since the Fowkes method divides the surface free energy into a polar and dispersive component, an analysis was performed regarding the variation of the components, again, using the two couples.

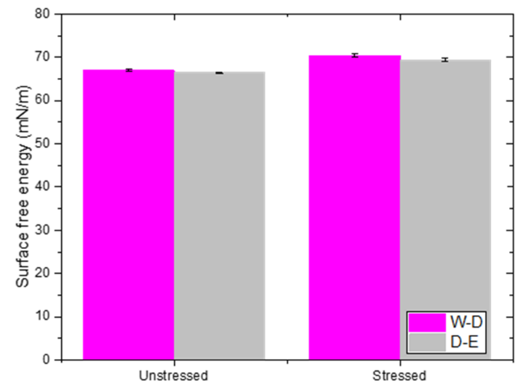


Fig. 9. Comparison of surface free energies on the unstressed and stressed regions determined via Fowkes methods using couples of water - diiodomethane (W-D) and diiodomethane - ethylene glycol (E-D)

In fig. 10 a chart shows the average values of the polar and dispersive components of the unstressed and stressed regions.

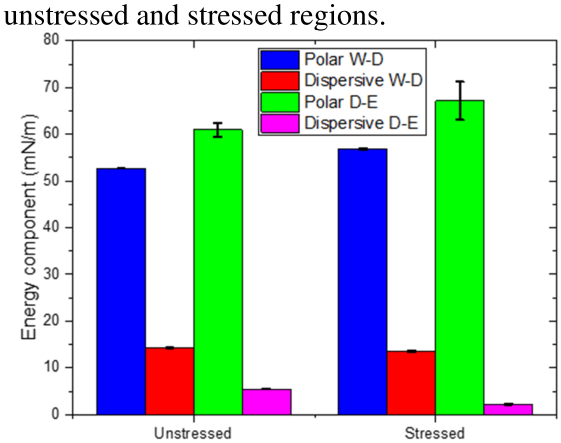


Fig. 10. Comparison of surface free energies components on the unstressed and stressed regions determined via Fowkes methods using couples of water - diiodomethane (W-D) and diiodomethane - ethylene glycol (E-D)

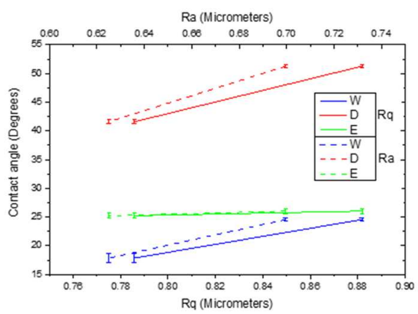
First we analyze the differences in the energy components determined using the W-D couple. An increase in the value of the polar component for the stressed region is observed: the unstressed region has a polar component of 52.70±0.04mN/m while the stressed one 56.91±0.11mN/m. The dispersive component of the unstressed region averaged 14.31 ± 0.04mN/m while on the stressed region

13.51±0.11mN/m, in this case a decrease being recorded.

For the E-D couple the polar component for the unstressed region averaged 60.92 ± 1.50mN/m and on the stressed region 67.15±4.13mN/m, thus an increase was observed from unstressed to stressed surface. The dispersive component for the unstressed region is 5.50±0.10mN/m while for the stressed one 2.27±0.15mN/m, a decrease is observed.

Both couples suggest that on the stressed region the polar component registers an increase in value while the dispersive component decreases. The amplitude of these variation are related to the polar and dispersive components of the liquids used.

The contact angle values and for water and diiodomethane appear to be strongly correlated with the change in surface roughness, as observed in Fig. 11.



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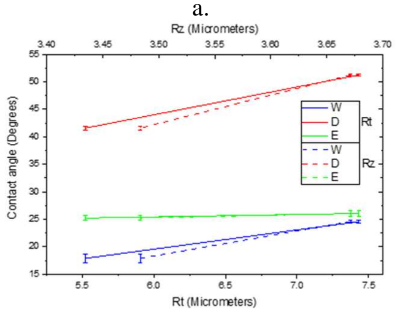

b.

Fig. 11. Correlation between contact angle and roughness parameters

As the roughness parameter value increases, so does the contact angle value for water and diiodomethane, in this case a rougher surface relates to an increased surface wetting. The contact angle for ethylene-glycol appears not to be influenced by change in surface roughness.

The observations on the influence of the roughness on the contact angle values can be extended to the surface free energy in a reverse manner: as the surface roughness increases, the surface free energy decreases.

4. CONCLUSION

An assembly that replicates the fracture fixation of a humeral defect was tested and the mechanical behavior was evaluated. Despite that the loading during the test was compressive, the bone fixation plate was loaded in bending. The bone plate suffered plastic deformations that produced damage of the anodized layer, the surface characteristics of these regions were determined.

The roughness parameters Rq, Rt, Rz and Ra showed a decrease in value on the stressed region. Rt showed the highest variation, the changes in surface topography were caused by a flattening of peaks and valleys by plastic deformation, assumption sustained by the decrease of Rku and Rsk - an indication of a symmetrical distribution of peaks and valleys.

An enhancement in surface wetting was observed on the stressed regions which was associated with the increase of the surface free energy of the material. This increase in energy makes the surface unstable and prone to chemical reactions, more susceptible to corrosion.

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ANALIZA SUPRAFEȚEI UNEI PLĂCI DE TITAN UTILIZATĂ PENTRU FRACTURA HUMERUSULUI DUPĂ TESTAREA MECANICĂ

Rezumat: Fracturile humerale proximale sunt frecvent întâlnte în practica clinică. Scopul acestui studiu a fost de a testa din punct de vedere mecanic și al proprietăților de suprafață un model de placă osoasă din titan anodizat prin simularea unui ansamblu care reproduce fixarea fracturii unui defect humeral. Ansamblul experimental a fost alcătuit dintr-un os artificial în care a fost creat un defect prin îndepărtarea unei regiuni osoase. Defectul a fost remediat folosind o placă osoasă. Ansamblul a fost testat la compresiune pentru a se analiza comportamentul mecanic. În timpul testării la compresiune, placa osoasă a fost solicitată la încovoiere, stratul anodizat de pe suprafață a cedat și regiunile solicitate au devenit evidente. Rugozitatea și umectabilitatea suprafeței plăcii osoase au fost testate înainte și după testarea mecanică. Am constatat că proprietățile de suprafață ale plăcii osoase s-au modificat ca urmare a solicitării mecanice. Această modificare a morfologiei suprafeței joacă un rol important în interacțiunea implant - țesut, deoarece umectarea suprafeței și energia liberă a suprafeței sunt influențate în mare măsură de forțele mecanice care acționează asupra implantului după procedura chirurgicală de implantare.
Cuvinte cheie: titan, placă osoasă, test de compresiune, rugozitate, umectabilitate, interacțiune.

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