Enhanced Wear Resistance of Ball-and- Socket Joints of Dental Implants by Means of Titanium Gaseous Nitriding

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ABSTRACT: The aim of this research is the surface hardening of the ball-and-socket joint of dental implants by means of heat treatments in order to obtain titanium nitrides. These nitrides minimize the wear of the titanium used in prosthesis. In this paper the optimum heat treatment, the hardness and the wear resistance are described in relation to the ball-and-socket joint without heat treatment.

KEY WORDS: ball-and-socket joint, wear, titanium.

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INTRODUCTION

The functionality of a complete, well-designed and well-built prosthesis is determined by three factors:

- Fitting: it is the marginal adaptation of the prosthesis by means of peripheral sealing obtained with correct microstate and myofunctional impression to achieve a good finish and polishing of the edges, which shall avoid the accumulation of food remains between the prosthesis and the mucosa, and shall provide primary fixation of the prosthesis.
- Stability: the prosthetic stability is the ability to bear lateral loads that tend to displace the prosthesis from its rest position. Load is defined as the externally exerted force or the moment of force responsible for an internal tension state in the material. The best way to avoid the lateral loads that alter prosthetic stability is to achieve a bilateral balanced occlusion lacking individual contacts that cause the detachment of the denture.
- Retention: retention elements shall only be favourable if the prosthesis is basically stable. In total edentulous patients, retention is related to residual bone height. Loss of teeth implies continuous reduction of alveolar bone, which becomes faster if all teeth are missing and thus, retention diminishes. Patients with greater bone loss are those who obtain greater benefits from the placement of retentive elements on implants.

When the fabrication of a complete upper or lower prosthesis is acceptable from the clinical and prosthetic point of view, but the prosthetic retention is inadequate due to bone resorption, it is necessary to give the patient another alternative with the means within our reach, through restorations anchored to implants such as overdentures with bar attachments, ball attachments or ball-and-socket attachments, in order to increase prosthetic retention.

Prosthetic retention and stability shall provide the patient with security and comfort to speak and chew, since the masticatory force is increased when the prosthesis mobility and excessive pressure on spots on the mucosa that irritate support tissues are reduced.

Bite force in individuals with natural teeth is about 25–75 kg, whereas in patients with total dentures the exerted force is only of 5–16 kg, which is a significant limitation. Preskiel [1] found that by placing anchors to support the loads in the lower denture, without modifying the opposing upper denture, bite force was increased by 50%. Other researchers [2–6] also observed this increase when placing anchors. They also suggested
that the significant factor in this force increase was the increase in stability and retention.

Furthermore, greater levels of masticatory force were found in implant-supported overdentures than in root-supported overdentures. Spiekermann [6] observed that articulated superstructures on anterior implant-supported bars show lower load values than telescopic or ball attachments. They published [6] a review of patients suffering from atrophy of the mandibular alveolar crest and who had been treated with ball attachment-supported overdentures. Success rates of single cases (97%) and of dentures (100%) were very good.

The axial anchorages have been used for decades as abutments for overdentures and are the simplest ones to provide additional stability, retention and support, but they do not substitute in any way a denture fabricated and designed incorrectly. A badly built denture will move in the mouth around the implants, thus causing overloads and affecting the periimplant bone area. The ball-and-socket anchorage system has to be chosen before the surgical stage, because it requires a semi submerged technique (TSS) in implant delivery to perform a supragingival prosthetic attachment, and it is important to know the space available in the vertical and buccolingual sense to place the female part in the resin [7,8].

The ball-and-socket joint is a force-breaker attachment in a spherical design that rotates inside a Teflon® cap. It is formed by:

- The male part is constituted by a flat or 15° angled washer, a ball that is threaded to the external thread of the implant’s neck and doubly fixed by a screw in the upper part of the ball to the internal thread in the implant’s neck.
- The female part is an empty Teflon® structure set into the base of the denture, in contact with the tissues. Easy to place and change, it articulates with the male part, allowing rotation movements on the anchorage.

Masticatory pressures are absorbed by the Teflon® female part, without transmitting them to the implant’s surface, because the spherical shape of the ball-and-socket joint allows turning, compression and traction of the denture in the movements of chewing. Teflon® works as a resilient force-breaker system that can turn in all directions giving minimal torsion on the implant [3,9].

The height of the ball-and-socket joint is 4.3 mm, lower than the ball attachment’s height of 7 mm. This means a short lever arm that minimises torque on the implant, allowing us to fabricate a prosthesis
without increasing the vertical dimensions, keeping the parameters for the existing distance between both alveolar crests.

Ball-and-socket connection should be in line with the prosthesis insertion axis. To do so, the implant axis shall be corrected with the 15°-angled washer that permits six positions on the hex neck of the implant. This type of attachments, ball-and-socket joints, articulate through rotation translation with multiple degrees of freedom; but this freedom diminishes as it is combined with a second or more attachments, thus allowing only rotation on the sagittal axis. It tolerates a divergence of around 10° unparallelism between two units, greater divergences can result in loosening of the threads of balls and bone resorption. The minimum amount of ball-and-socket joints advised in the mandible is two, one on each side of the arch. Increasing the number of joints increases retention and enhances stability.

Ball-and-socket joints allow a denture movement that is not harmful. This movement is like a security valve for the implant. Each implant works correctly and independently. Ball-and-socket attachments are a prosthetic alternative in implant restoration of totally edentulous patients, in order to obtain a better function of the prosthesis when bone resorption is extensive. They are easy to connect, quick and hygienic, as well as economical, because they need few implants and sometimes they let us use the same prosthesis of the patient, thus obtaining the retention this same prosthesis previously lacked, allowing the patient to eat, speak, smile and yawn more securely.

However, one of the most significant problems with ball-and-socket joints is the wear they suffer due to titanium being a relatively soft material. This wear causes material loss to the surrounding tissues, as well as a great amount of metal ions that can affect the good long-term behavior of the dental implant. Furthermore, the wear facilitates electrochemical corrosion of the ball-and-socket joint. In Figures 1 and 2, worn ball-and-socket joints that need to be replaced are shown.

A mechanism to increase wear life of titanium is nitriding, since once titanium nitride (TiN) is formed, it increases strength of the joint from 220 Vickers units up to 1000 Vickers units. This treatment is totally inert with the tissues and favours sliding of the ball-and-socket, significantly avoiding wear [10].

MATERIAL AND EXPERIMENTAL METHOD

Grade 3 titanium ball-and-socket joints produced by Klockner were studied. Twelve thermal treatments were performed, with different times and temperatures, as detailed in Table 1.
Figure 1. Worn ball-and-socket joints.

Figure 2. Worn ball-and-socket joints.

The samples are left to cool down in the furnace after treatment, in order to obtain an alpha-grain structure, that allows making up for the increase in brittleness produced by nitriding.

The tests were conducted in a tubular furnace, with an alumina tube, capable of reaching 1300°C. So as to obtain a nitrogen atmosphere, a high-purity nitrogen cylinder was connected to the alumina tube, and the tube was kept closed during tests. An outline is shown in Figure 3.
Table 1. Temperatures and times of the treatments applied.

<table>
<thead>
<tr>
<th>T [K]</th>
<th>Time (h)</th>
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<tbody>
<tr>
<td>700</td>
<td>4 8 16</td>
</tr>
<tr>
<td>900</td>
<td>4 8 16</td>
</tr>
<tr>
<td>950</td>
<td>4 8 16</td>
</tr>
</tbody>
</table>

Figure 3. Experimental distribution of nitriding processes.

When the treatment is finished, the sample is prepared to study the microstructure and measure hardness and wear. Hardness tests were performed with a high-precision Matzszawa microhardness tester, applying a 1 kg load for 15 s. Wear tests were performed in accordance to ASTM standard on adhesive pin-on-disk tests in salivary medium at 37°C applying a load of 25 kg. As the wear test was being performed, gravimetric measures were controlled in order to determine the weight loss over time by means of a high-precision set of scales.

EXPERIMENTAL RESULTS

Metallographic Structure

The homogeneously nitrided ball-and-socket joint is shown in Figure 4. Observations under light microscope clearly show the existence of a superficial layer of about 100 μm on the sample, in which the only existent phase is α phase.

The thickness of the observed layer depends on the temperature and time of treatment. The greater the temperatures and times, the thicker
the observed $\alpha$-phase layer. The existence of this layer proves that diffusion of gaseous nitrogen towards the inside of the sample has occurred, since it is the only mechanism that can explain the existence of the observed $\alpha$-phase superficial layer [11–14].

**Hardness**

After examining the microstructures, we moved on to determining the hardness values of the samples both on the surface and in the cross section.

The hardness values obtained show a clear increase in superficial hardness in relation to the hardness of the untreated sample. In some samples, superficial hardness exceeded 1000 HV$_{500}$, as shown in Table 1. Figure 5 shows the hardness values in a cross section at different distances from the sample surface, of a sample treated at 950°C for 8 h. Note that hardness is maximum at the surface and diminishes down to 400 µm deep.

In all the diagrams, a fine correspondence is shown between the value obtained from the superficial hardness and the values of hardness at different distances from the surface obtained in the cross section, except in the data of samples treated at 700°C. This discrepancy can be due to diffusion at a temperature of 700°C being very low, so nitrogen did not
penetrate further than a few micrometers. In general, the good value correspondence confirms that no errors have occurred in superficial hardness measurement of the samples [15–16].

As we have already mentioned, it is shown that the diffusion of the samples treated at 700°C has been very low, since there was not a great increase in superficial hardness. At temperatures of 900°C and 950°C, however, the increase in superficial hardness is highly significant, as can be noted in Figure 6.

The study of the graphs that show the hardness values for different distances from the surface permits the estimation of the depth of nitrogen penetration into the sample, because, according to the theory, the increase in hardness is related to the presence of nitrogen in the sample.

From the graphs, the distance from the surfaces in which the hardness value is below 500 HV was taken as a limit for the effective nitrided layer (Table 2), since it is a hardness value that cannot be reached by means of thermal treatment of titanium. This has been taken as a convention to compare samples, because penetration distance of nitrogen is quite greater than what convention states.

From this convention, it is observed that, as an average, the thickness of the effective nitrided layer is about 60–100 μm. If a graph of the thickness values of the nitrided layer versus the treatment temperature and time is made (Figure 7), the strong relationship that exists there is shown, since with greater temperatures and/or times, the thickness of
Figure 6. Superficial hardness values in relation to the treatment temperature and time. Superficial hardness (HV).

Table 2. Superficial hardness values of treated samples, in HV$_{500}$.

<table>
<thead>
<tr>
<th>T [°C]</th>
<th>t[h] 1</th>
<th>4</th>
<th>8</th>
<th>16</th>
</tr>
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<tbody>
<tr>
<td>700</td>
<td>413</td>
<td>544</td>
<td>717</td>
<td>547</td>
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<td>950</td>
<td>1018</td>
<td>1028</td>
<td>967</td>
<td>1097</td>
</tr>
</tbody>
</table>

Figure 7. Thickness of effective nitrided layer vs. treatment temperature and time. Layer thickness (μm).
the nitrided layer increases, as is expected from the characteristics of nitrogen diffusion process.

Wear

After studying the microstructure and measuring the hardness of the samples, abrasive wear tests were conducted in order to check the efficiency of the gaseous nitriding treatment in wear reduction.

In each one-sample test, seven wear values were obtained in an interval of 60 min. This permits checking that there is no problem affecting the test, and following up the wear process throughout the test. Figures 8–10 show the wear curves of the 12 samples tested and they are compared to the results obtained from the wear tests of an untreated sample.

The wear data obtained in the tests show reductions of over 2/3 in the wear suffered by the samples treated by means of gaseous nitriding, in relation to untreated samples. So we can say that the treatment is valid to obtain a decrease in wear in Ti parts.

If treatment temperature and time values, and the total wear suffered during the wear test by the sample are represented at the same time, it is seen that, although in general the greater the hardness, the lesser the wear, and the minimum wear value is not at the point of maximum treatment temperature and time, but at an intermediate point.

This fact may be due to the effect of increased brittleness that nitrogen produces when the composition percentage of nitrogen in the

Figure 8. Graphs of the wear values of samples treated at 700°C. Untreated sample.
Figure 9. Decrease in weight by wear of the samples treated at 900°C. Untreated sample.

Figure 10. Decrease in weight by wear of the samples treated at 950°C. Untreated sample.

titanium alloy is excessively increased. This hypothesis explains the fact that, although the hardness is greater for treatments under maximum temperature and time, wear reduction does not follow the wear theory, but it presents a minimum saddle on the surfaces of Figure 11.

Minimum wear value is between a treatment at 900°C for 8 h and a treatment at 950°C for 1 h, as shown in Figure 11.
This decrease in wear allows that this hardening treatment is useful in applications that, without having a constant wear, require additional protection against wear, or in applications in which loads are light or medium.

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REFERENCES