Microscopic Assessment of Damage to Miniplates for Mandible Osteosynthesis

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Abstract. Degradation processes of implant materials have a significant effect on the reactions taking place around them. Processes related to mechanical wear, corrosion and tribological wear can be distinguished here. The phenomenon of fretting has a particularly significant impact on changes around the implant. Destruction of materials' surface layers by fretting occurs in biomedical implants. Oxide formation was observed in the friction zone. Wear products remain in the area of contact, inside the fretting corrosion pit, until they accumulate in excess and leave the area of contact. In fretting, oxidation may be a factor protecting against wear, when a wear-resistant oxide layer forms on metal surfaces at high temperatures. The presence of NaCl in the tissue environment intensifies the progression of fretting corrosion.

Keywords: Degradation processes · Plate fixations · Microscopy

1 Introduction

Setting and immobilizing bone fragments is an important therapeutic problem in facial bone fractures. In an insufficiently immobilized fracture, the gap widens and healing (union) is delayed. If fragments are shifted constantly, the healing process is severely disrupted. The introduction of stable osteosynthesis provides better stabilization of bone fragments, enables further functional treatment without the use of intermaxillary (maxillomandibular) fixation, and shortens the time of treatment. The application of micro- or mini-plates in treating facial bones is currently considered to be one of the most effective methods of maxillofacial surgery. Osteosynthesis by means of miniplates is recommended in all cases of mandibular fractures. These plates are made from titanium and its alloys.

As a result of tribological wear and/or corrosion wear processes, metallic implants may be an "emitter" of many chemical elements and compounds harmful to human health and cause illnesses defined as "metalloses". Marciniak's

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research demonstrated that a connective tissue capsule is formed and osteolytic processes (bone atrophy) develop as a consequence of the development of biocorrosion [10,14,17,18]. Peri-implant osteolysis is a complex biochemical process strictly linked to an implant's mechanical functioning [1]. Activation of osteoblast differentiation is stimulated by cytokines released by macrophages as a result of phagocytosis of hydroxyapatite and polymethylmethacrylate (PMMA) particles as well as of metal originating from the implant [1,9,10]. Reports in the literature show that wear products of metallic implants and chronic tissue inflammation are linked to the excessive presence of toxic elements. Parts of osteosyntheses are particularly susceptible to tribological and corrosion wear processes. The accumulation of particles and ions of metallic elements in surrounding tissues are the results of implant materials' degradation processes. It is observed in the case of both austenitic steels and titanium alloys, considered to be highly biocompatible. Reduction of the effects of tribological and corrosion wear of metallic implants is one of the main subjects of research conducted in many scientific centers [15,17]. A better understanding of the phenomena and mechanisms of tribological and corrosive destruction of materials at moving joints of systems serving to stabilize bone fractures will allow for assessment of the impact of environmental factors in the human body on these processes of materials' degradation. The presence of biofilm on metal surfaces may alter the mechanisms of and drastically accelerate corrosion processes. The effect that biofilm has on friction and wear processes of implant materials is also not without significance, as mentioned earlier. The influence of saliva and biofilm on initiation of fatigue cracking of parts in osteosyntheses must be explained. Aerobic microbes intensify the formation of cells of varying oxygenation, which fosters the development of crevice corrosion. In turn, the presence of anaerobic bacteria in the layer of biofilm aids the development of pitting corrosion of metals. Under such conditions, hydrogen may be released as a result of complex biochemical transformations, leading to unfavorable metal hydrogenation phenomena (hydrogen embrittlement). Data concerning intensive hydrogen absorption by implant titanium alloys in a biological environment can be found in professional literature. This leads to reduction of plasticity, changes of structure and grain size (refinement), and reduction of the fatigue strength of titanium implants. It should be noted that there is no data in the literature about tribological degradation of materials used in bone fixations, particularly in a biological environment [2,7,10,12,13].

After analyzing reports in the literature concerning interactions between implants and surrounding tissues, one can observe that problems linked to peri-implant reactions have not been unambiguously explained. The goal of this paper is to characterize the degradation processes taking place in plate fixations of the mandible.

2 Research Materials and Methodology

15 mandible fixation plates were tested after the treatment had been completed. Fixation plates was made of Ti6Al4V titanium alloy - Fig. 1. The system consisted of plates and inter-operating bolts that were present in the human body

Fig. 1. View of mandible fixation plate tested as discussed below

for a period of about 3 months. Tests were conducted with the consent of the Local Ethical Committee for Animal Testing in Białystok.

Miniplates were observed from the perspective of surface wear, and their chemical composition was tested by means of an HITACHI S-3000N scanning electron microscope equipped with an NSS (Noran System Six) X-ray microanalyzer.

Analysis of the structure of the surface layer after fretting and fretting-corrosion was also conducted using an FIB (Focus Ion Beam system) microscope [5]. An Hitachi NB5000 double-beam scanning microscope equipped with a Ga+ ion source, with a maximum acceleration voltage of 40 keV and beam current up to 80 nA, was used in investigations.

The surface of the deformed conical seat was conducted using an 3D confocal laser microscope LEXT OLS 4000.

3 Research Results and Discussion

Ensuring the proper durability of implants in the environment of tissues is a very important engineering and clinical problem. The following figure among the dominant processes of biomaterials' degradation: corrosion, mechanical damage and tribological wear, particularly under conditions of so-called fretting [8]. Processes related to fretting, i.e. friction between two apparently permanently joined parts due to micro-displacements, are the most dangerous and the least understood [3,11]. These processes are intensified under the influence of an aggressive biological environment with significant participation of saliva or so-called biofilm.

The plate's surface, in its initial state, may undergo a change as early as during the technological process of its manufacturing due to local damage to the implant's passive layer. Plate wear in the form of scratches is also observed, leading to a change in hole shape. All conditions required for fretting to occur are met in a plate fixation of bone, and various wear mechanisms accompany fretting, particularly abrasive (fretting-wear), corrosive (fretting-corrosion) and fatigue (fretting-fatigue) mechanisms. The destructive action of fretting is intensified by loosening of bolts as well as by damage to the passive layer [4,6,16,18].

It should be emphasized that deformation of plate seats may lead to instability of the entire system. This is a very unfavorable phenomenon due to the probability of a reaction on the implant – tissue interface. Changes to the design of the fixation system and introduction of changes to its manufacturing process should be considered due to its susceptibility to fretting.

In the case of large deformations, greater plate wear is observed, meaning that wear products migrated to surrounding tissues. Wear products are very fine and can migrate via diffusion to many internal organs, such as: the lungs, kidneys, liver, brain and bone marrow.

However, the greatest threat is micro-crack initiation in bone plates when they are primarily, and unskillfully, modeled. This threat is very real when modeling is performed on a segment already weakened by holes. Initiated micro-cracks propagate very rapidly, resulting in the risk of further destruction of implants. Implant destruction is further facilitated by the stress state, which leads to accelerated development of corrosion in areas of stress concentration.

The results of a'posteriori investigations of parts of plate stabilizers used to make fixations indicate characteristic traces of damage. These traces include damage to the surface layer of coned seats, and to a lesser extent, damage to flat surfaces of plates.

Traces of abrasive wear, primarily due to micromachining, are formed during rotation of joining bolts and bone screws while their conical heads are pressed into their seats in plates. This unambiguously indicates the form of wear and the areas where it is present. Only the passive layer on surfaces undergoes abrasion. Wear processes develop with particularly intensity in areas of micro-contact between joining elements. Self-unscrewing of bone screws under the influence of low-frequency variable loads that a stabilizer is subject to during the period of its use, also cannot be ruled out as a cause of abrasive wear.

Damage of the second type is characteristic of corrosive destruction processes. It occurs at points of contact between interlocking parts (stress concentration). Corrosion pits have a decisive contribution to the process of surface layer destruction, and their sizes are much larger than in the case of mechanical wear. Corrosion pitting is the greatest in areas where scoring (abrasion) is present, which is typical. This means that the process of corrosive destruction is initiated and, to a large degree, activated by damage of the first type. It is precisely in these areas where the passive layer is destroyed and pitting corrosion develops. Moreover, tribo-corrosion (friction corrosion) processes, augmented by pitting corrosion, take place at points of contact. Tribo-corrosion is caused by mutual micro-displacements of contacting parts. Such displacements may occur as a result of insufficient tightening or loosening of joining bolts, and they may also be the result of elastic deformations of elements. Crevice corrosion does not have a decisive effect on the total size of corrosion losses, due to its slow rate of progression.

The conducted observations indicate that damage of the first type, probably occurring during the surgical procedure itself when the stabilizer was mounted, is the most frequently observed (Fig. 2).

Figure 3 presents damage of the second type. Visible fine wear particles may intensify secondary abrasive wear processes. Greater wear on elements of the stabilization system in the single-plate fixation is due to the nature of this fixation's operation. It is exposed, above all, to bending and torsion loads. The largest areas of wear are observed on interlocking surfaces of the plate seat and head of the last screw found in bone, which is caused by greater mobility.

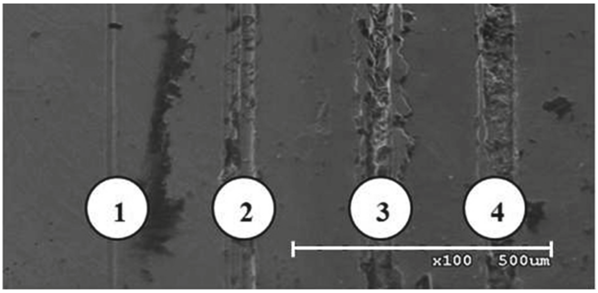


Fig. 2. Photograph of bolt surface with visible damage of the first type

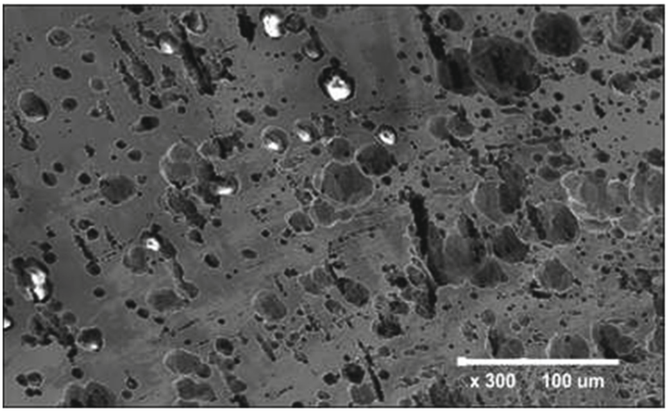
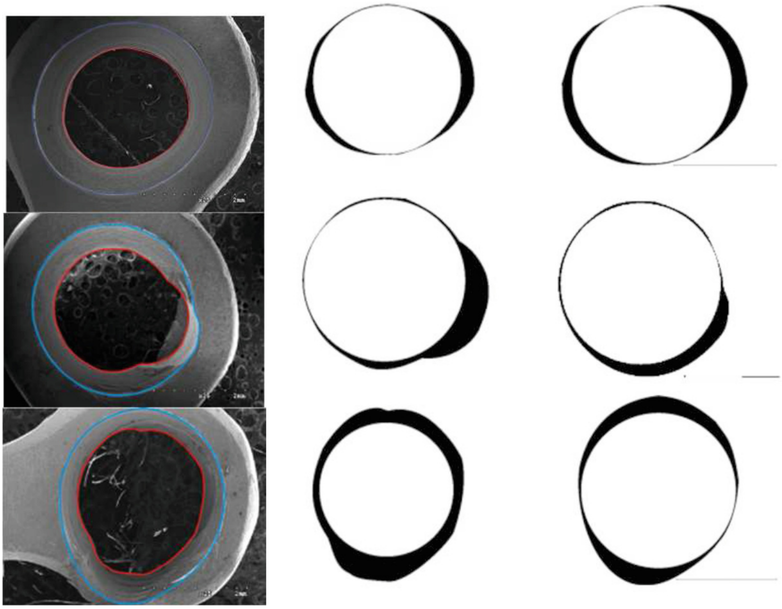


Fig. 3. Photograph of plate surface with damage of the second type

Examinations of plate surfaces under a microscope revealed visible corrosion pits formed as a result of the interaction of bodily fluids on the metallic material. Moreover, the presence of wear particles is visible on the plate's surface. These are metal oxides formed as a result of abrasion and/or adhesive interactions. The degree of wear and deformation of holes in the plate are shown in Fig. 4.

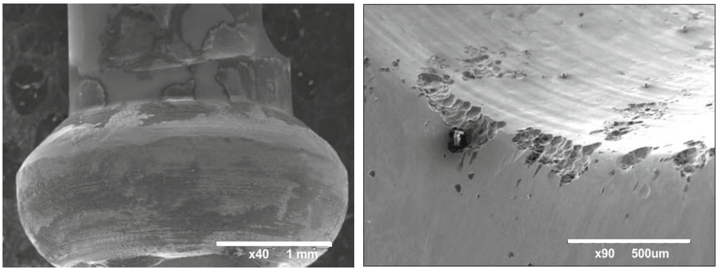
The development of corrosion is observed near holes as a result of the action of the aggressive environment. Numerous discolorations (Fig. 5a) and corrosion pits (Fig. 5b) are visible on the surface. Traces of abrasive wear can also be found near holes. In addition, deformation of hole shape is very frequently observed. Both processes occur when screws are screwed in and as the implant is used after that.

Over the course of observations of fixation elements under a microscope, much damage caused by fretting processes was visible. Fretting losses were formed on the surface of the screw as a result of micro-displacements accompanied by elastic deformations occurring between fixation elements. These are characteristic pits. In addition, discolorations formed on the screw surface that was in contact with surrounding tissue, and traces of pitting corrosion are visible. The action of



(a) (b) (c)

Fig. 4. Example results of investigations of screw seat deformations in fixing plates (a) initial image, (b) changed image for interior hole diameter (c) changed image for exterior hole diameter

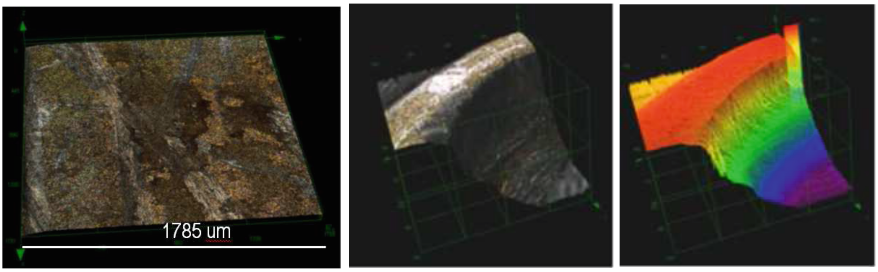


(a) (b)

Fig. 5. Photograph of plate hole surface: (a) discolorations, (b) corrosion pits

the surrounding environment, of reduced pH, and the presence of ions, mainly chloride ions, were the factors initiating the development of pits.

Observations of plate seats revealed damage to the surface layer in the form of abrasive wear. The scratches and ridges visible on the presented photograph are indicative of this. The plastic deformation that can be observed most probably occurred during the mounting procedure. Figure 6 presents the results of plate assessment using a LEXT OLS 4000 3D confocal laser microscope. The central part of the plate, on which traces of wear are visible, was subject to assessment.



(a) (b) (c)

Fig. 6. 3D view: (a) of the corrosion pit analyzed above, (b), (c) of part of the conical seat in the miniplate

Traces of friction were imaged and measured, and the depth, width and slope of these traces were assessed, along with average values arising from the capability of measuring multiple profiles.

Figure 6b, c presents a part of the conical seat in a fixing miniplate after the period of its use. Both changes of the surface layer and changes in the seat itself are visible here. The surface of the conical seat was deformed and sustained losses due to corrosion as well as fretting. The complex phenomenon that is fretting corrosion took place here. This phenomenon is still not fully understood and is practically unknown in the context of osteosyntheses. Understanding it and describing wear mechanisms will make it possible to prevent much damage occurring in bone fixations. Furthermore, the presence of a morphological texture was observed at a depth of approx. 1.5 μ m (Fig. 7). This texture was formed by plastic deformation generated over the course of friction processes. The presence of a crack oriented parallel to the surface, marked with an arrow, was observed just under the sample's surface. The thickness of the material above the crack, depending on the point of observation, ranged from approx. 20 to approx. 100 nm.

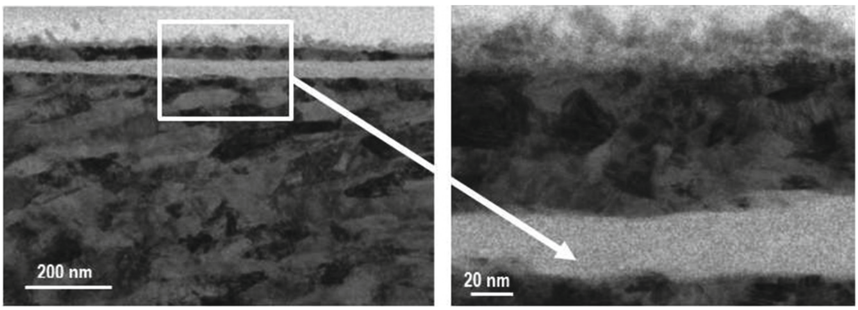


Fig. 7. Morphological texture along with layer formed as a result of tribo-corrosion processes at a depth of approx. 1.5 μ m

4 Summary

Various types of degradation processes are observed in facial bone fixations. Besides mechanical and corrosion damage, tribological damage can also be seen. The greatest wear processes are generated as a result of fretting. Fretting is a very complex process that results in various types of destruction, which have very significant consequences. Nearly a century has passed since the first reports of this type of destruction, but despite this fact, scientists still cannot come to an agreement and provide a clear definition of this process. Some believe fretting to be a type of wear or corrosion, while others believe it to be a type of friction occurring under specific conditions. In our opinion, it seems more justified to define fretting as a specific type of friction between two surfaces subjected to load and remaining in constant contact. To expound on the above, it is justified to distinguish the following component processes: fretting wear, fretting fatigue, fretting corrosion. The surface layer of elements may undergo fretting corrosion. Corrosion wear is linked to oxygen diffusion and grows along with load and friction path. In fretting, oxidation may be a factor protecting against wear, when a wear-resistant oxide layer forms on metal surfaces at high temperatures. The presence of NaCl in the tissue environment intensifies the progression of fretting corrosion.

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