POLISH ACADEMY OF SCIENCES - COMMITTEE OF MATERIALS SCIENCE
SILESIAN UNIVERSITY OF TECHNOLOGY OF GLIWICE
INSTITUTE OF ENGINEERING MATERIALS AND BIOMATERIALS
ASSOCIATION OF ALUMNI OF SILESIAN UNIVERSITY OF TECHNOLOGY
Conference Proceedings
12th INTERNATIONAL SCIENTIFIC CONFERENCE
ACHIEVEMENTS IN MECHANICAL & MATERIALS ENGINEERING

Corrosion of steel implants electrically stimulated

J. Szewczenko, J. Marciniak

Silesian Technical University,
Institute of Engineering and Biomedical Materials,
Konarskiego 18a, 44-100 Gliwice, Poland

The paper presents investigation results of the influence of various methods of a bone union electrical stimulation on the corrosion progress of implants from the AISI 316 L steel, coated with the passive and passive-carbon layers. The electrical stimulation was carried out for 28 days in the Tyrode's physiological solution. Direct, pulsating, sinusoidal and impulse currents were used for the electrical stimulation. Mass reductions of implants and corrosion damages developed on their surfaces were evaluated for the particular methods of electrical stimulation. Moreover, results are presented of the investigation of the implants' corrosion products infiltration, resulting from the stimulation of a bone union with the direct electrical current using the invasive method.

1. INTRODUCTION

The electrical stimulation of the osteosynthesis process is aimed at activating the reconstructive processes of the bone. Numerous tests with animals and clinical experience show that this method is applicable for activation of bone reconstruction in the following cases: non-union of bone fragments [1], delayed union of fractured bone [2], pseudarthrosis [3], and in case of pathological fractures [4]. Employment of electrical stimulation not only speeds up union of fractured bone but also reduces painfulness of the injury locus [5], and suppresses development of micro-organisms [6]. It should be stressed that the electrical stimulation is purposeful at the initial stage of the fractured bone treatment, when the load improvement of the union is not possible or difficult, then the current passing through the bone tissue reconstruction zone substitutes the action currents. During the load improvement phase the natural electro-mechanical processes are turned on.

Research work of the authors demonstrated that the electrical stimulation of the fractured bone union with the direct current using the invasive method leads to development of the pitting corrosion on electrodes featuring anodes in this method [7].

Previous research of Marciniak [8] demonstrated that in consequence of corrosion development, the connective tissue capsule forms near the implant, with the phagocytic reaction and multiplication of collagen fibres, their hyalinization and metalosis occur. Therefore, advantages arising from the electrical stimulation of the fractured bone union become controversial when it leads to development of the implants' corrosion processes. This issue calls for the detailed explanation and has become the goal of the research carried out.

2. METHODOLOGY AND SCOPE OF INVESTIGATION

The following fractured bone union electrical stimulation methods were used in the investigations: the non-invasive, the semi-invasive, the invasive.

Specimens from the AISI 316L steel were used in the investigations, with the passive, passive-carbon surfaces and the cortical bone screws with the passive-carbon coating. The passive surface was left in specific areas on specimens and bone screws with the passive-carbon coating, which was intended to direct the current passage [16]. The stock material was in form of bars. Machining of the specimens' surface, their grinding, electrolytic polishing, chemical passivation and deposition of the carbon coating was carried out in the experimentally determined conditions [3].

The purpose-designed test stand was developed in house to realize the investigations, making it possible to carry out the electrical stimulation with various methods in conditions close to the physiological ones [16].

The investigation of the effect of the electrical stimulation of the fractured bone union on the corrosion process of the implants with the passive coating and with the passive-carbon one was carried out for different current characteristics. The electrical stimulation for each surface variant and current type lasted 28 days. Effect of electrical stimulation on specimens' condition was evaluated after each seven days long cycle. The specimens were weighed with the accuracy of $5\ 10^{-5}$ g and their surfaces were examined in the scanning microscope. After conducting the electrical stimulation process, the metallographic microsections were made from the specimens and examined on the light microscope.

Moreover, 12 calf bones were used in the experiments. Stimulation with the direct current with the invasive method lasted 28 days. A mass loss of the electrodes was measured with the accuracy of $5\ 10^{-5}$ g and examinations were carried out in the scanning microscope of corrosion defects of the bone screws' surfaces.

After the 28 days long stimulation bone fragments were sampled from places near anode and cathode. The specimens were sprinkled with carbon, and the bones' chemical composition examinations were made afterwards in the X-ray micro-analyzer. The following chemical elements were accounted for in the analysis: Si, P, Ca, Cr, Mo, Ni, and Fe.

The electrical stimulation experiments were carried out in the following conditions:

- direct current with the current intensity $i = 40 \pm 0.5\ \mu A$,
- pulsating unidirectional current with the 29 Hz frequency, current intensity $i = 80 \pm 0.5\ \mu A$, with the equal current impulse and interval time lengths,
- sinusoidal current with the 20 Hz frequency and amplitude $i = 40 \pm 0.5\ \mu A$,
- series of alternate pulses $A\exp(t/t_0)$ with the time constants $t_0 = 0.2$ s, 1Hz frequency and amplitude $i = 80 \pm 0.5\ \mu A$,
- Tyrode's solution temperature $T = 36.6 \pm 1°C$,
- pH of the solution changing in the 7.6÷8.6 range.

3 Investigation results

3.1. Electrical stimulation with the direct and unidirectional pulsating current

Mass measurements of the specimens with the passive and passive-carbon coatings, made at the 7 days long intervals, did not reveal mass changes of specimens used in the non-invasive and semi-invasive electrical stimulation methods, no mass changes of specimens featuring cathodes in the invasive method were observed either.

Macroscopic examinations of specimens after 7 days of electrical stimulation revealed local etchings on their surfaces. The surface of etching increased with time, however, after 28 days of electrical stimulation, it was only an insignificant portion of the specimen's surface. The etchings occurred most often on the passive surface close to the specimen edges - fig.1b. It was found out, basing on examinations of the transverse metallographic microsections, that etchings had the surface character only.

Corrosion products in the form of a compact bowl, located over the developing pit, were observed on surfaces of specimens with the passive and passive-carbon coatings, featuring anodes in the electrical stimulation of the fractured bone union with the invasive method.

Pits on surfaces of electrodes the passive surfaces are characterized my small area size - fig.2a. Examinations of the metallographic microsections revealed that the corrosion defects reach up to 2 mm in depth - fig.2b. Moreover, corrosion defects characteristic for the inter-crystalline corrosion were found around pits localized at the air-Tyrode's solution border - fig.2c.

Corrosion defects occurred on the passive and carbon surfaces alike on specimens with the passive-carbon coating used as anodes in the invasive electrical stimulation method. Coating destruction took place around pits developed on the carbon surface. The shape and localization of the defect were related to the shape and localization of the corrosion products' bowl present on the specimen. The pits developed on the carbon surface were characterized by larger area size and smaller depth (1.5 mm) than occurring on specimens with the passive coating - fig.3.

Measurement of masses of anodes with the passive and passive-carbon coatings, used in the invasive method, revealed increase of the mass loss as a function of time according to the Faraday's law.

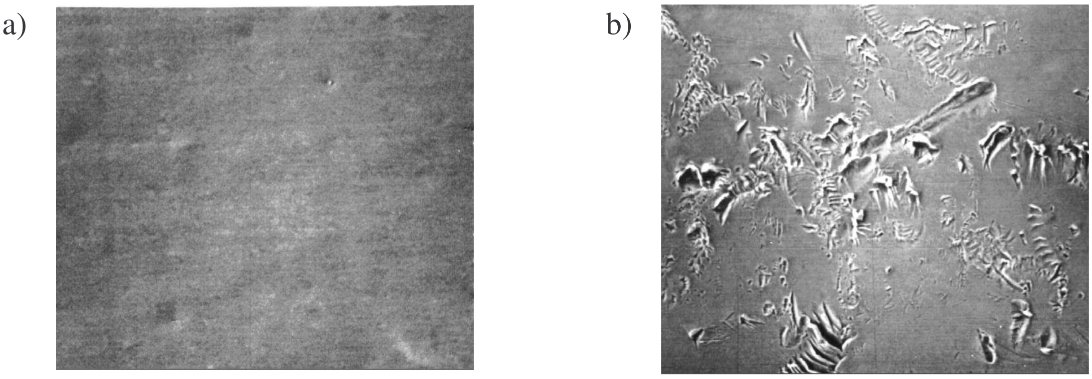

Fig.1. Specimen's surface with the passive layer after 28 days of electrostimulation, SEM, magnification 500x, a) average surface, b) local etched area of specimen

3.2. Electrical stimulation with the sinusoidal and pulse current

On the basis of measurements of the specimens' masses, with the passive and passive-carbon coatings no changes in the specimens' masses were observed.

Examinations of specimens, both with the passive and passive-carbon coatings, after 7 days of electrical stimulation, revealed local etchings on surface. Character and localization of these etchings were analogical to the ones occurring in case of the electrical stimulation with the pulsating direct current used in the non-invasive and semi-invasive methods - fig.1. The area of etchings totalled to an insignificant portion of the entire specimen surface.

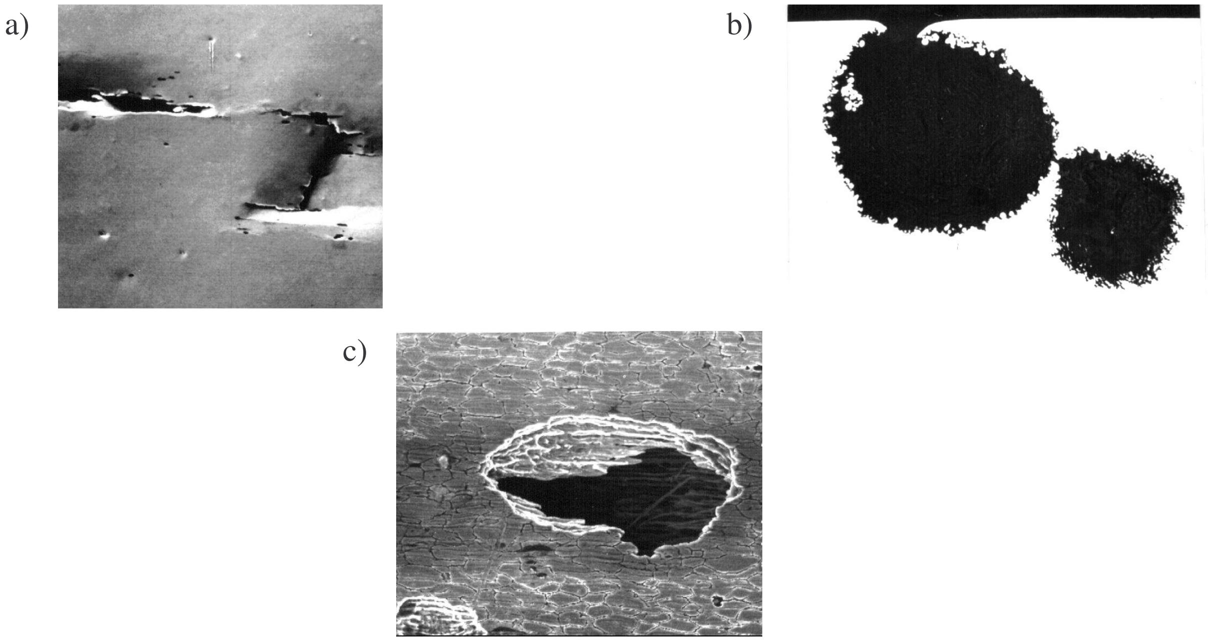

Fig. 2. Corrosion damage of the anode with the passive layer after 28 days of electrostimulation; a) damages on the sample’s surface, SEM, magnification 300 x, b) crosswise structure of the pit, light microscope, magnification 100 x, c) corrosion damages characteristic for the pit and intercrystalline corrosion, SEM, magnification 400 x

3.3. Electrical stimulation using direct current with the invasive method in bones

Examinations of the bone screws' surfaces, featuring anodes in the invasive method of the electrical stimulation of fractured bone union revealed that corrosion damages occur on their surfaces - fig.4a. They were observed both on surfaces coated with the passive and carbon layers alike. Defects of carbon-coated surface had larger area sizes and were characterized by smaller depths, compared with the passive coated surface. Small surface etchings were found on surfaces of bone screws featuring cathodes - fig.4b. These etchings occurred on passive-coated surface only.

Mass loss was detected in measurements of anodes' mass. The loss volume grew with the electrical stimulation time, according to the Faraday's law. Cathode mass did not change.

Dark overcolourings were found during macroscopic examinations in compact bone near anode. No noticeable changes were found near cathode. Total destruction of the spongy zone was found after cutting the bone across.

Examination of the chemical composition of the compact zone of the bone, sampled from the location near the cathode, did not reveal any metallic chemical elements. Analysis of the chemical composition of the bone specimen sampled from the location near the anode, revealed the significant atomic concentration of the metallic chemical elements

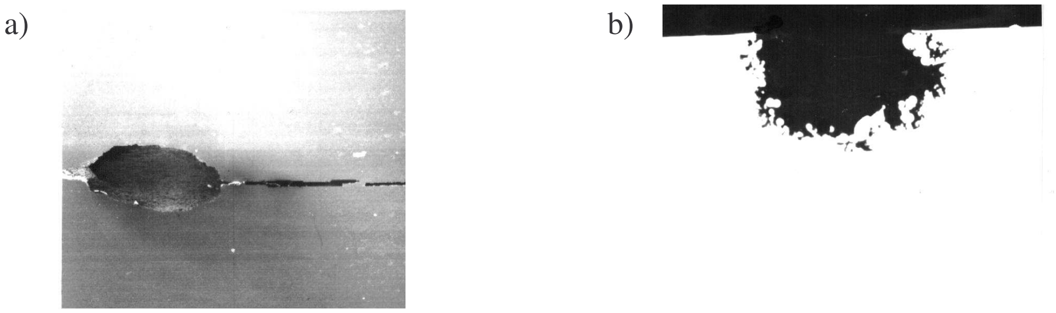

Fig. 3. Corrosion damages of the anode with the passive - carbon layer after 28 days of electrostimulation; a) damages on the sample's surface located near the interface passive-carbon – passive layer (suitably left and right side), SEM, magnification 25 x, b) crosswise structure of the pit, light microscope, magnification 100 x

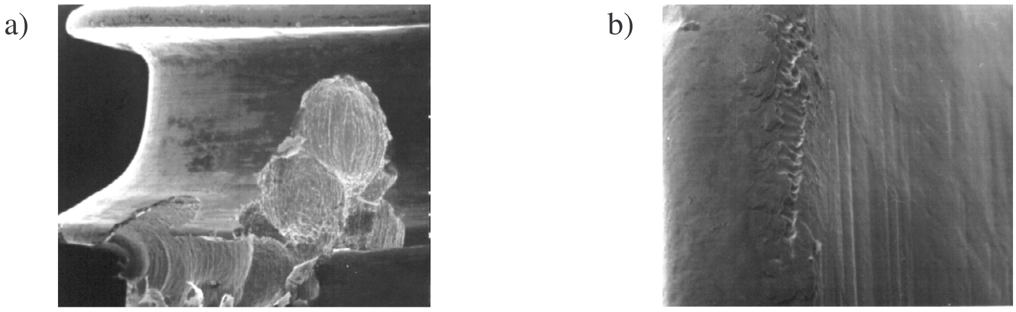

Fig. 4. Electrodes' surfaces after 28 days of electrostimulation; a) corrosion damages on the anode's surface with carbon layer, SEM, magnification 200 x, b) locally etched areas on the surface of the sample with passive layer, magnification 32 x

To evaluate the size of the corrosion products' infiltration area, examinations of the bone chemical composition were made along its outer edge, every 0.25 mm.

The maximum atomic concentration of Cr was 23.65% and occurred at the distance of 0.5 mm from the anode's surface in the opposite direction in respect to the current passage. The maximum distance of the Cr atoms occurrences was 4 mm and 5 mm, for the direction conforming to and opposite to the current passage direction respectively.

The maximum concentration of the Fe atoms, equal to 17.07% occurred in the direction of the current passage at the distance of 1.4 mm. The Fe atoms occurred up to 7 mm from the anode in the direction conforming to the current passage, and up to 11 mm in the opposite direction.

At the distance of 1 mm in the direction opposite to the current passage, the maximum atomic concentration of Mo was encountered, reaching 3,5%. The Mo atoms occurred on both sides of the anode, reaching the distance of 5.5 mm.

The Ni atoms occurred in the direction of the current passage up to 2 mm from the anode's surface, whereas, in the opposite direction they reached up to 7.5 mm. The maximum atomic concentration of Ni was 2.1% and it was found in the direction of the current passage at the distance of 1.5 mm.

4. CONCLUSIONS

Basing on the investigations carried out the following generalizations were formulated:

1. electrical stimulation of the fractured bone union, with the non-invasive and semi-invasive methods, using the pulsating direct current and the variable sinusoidal one, does not cause any mass change of the specimens with passive and passive-carbon coatings. The character of the observed changes indicates, that these methods may be used for electrical stimulation of the fractured bone union.
2. no mass losses in specimens with the passive and passive-carbon coatings, employed in the invasive method of the electrical stimulation of fractured bone union, and occurrences of only minimal local fogging of the specimens' surfaces, indicate to the applicability of this method also.
3. employment of the electrical stimulation of the fractured bone union with the pulsating direct current, causes mass losses of anodes, both for the specimens with the passive and passive-carbon coatings; their volume is in accordance with the Faraday's law. Therefore, the invasive method is inadmissible both for electrodes coated with the passive and passive-carbon layers alike. stimulation of the fractured bone union with the direct current with the invasive method leads to developing of the corrosion damages on surfaces of the bone screws, used as anodes. Surface etchings only were observed on cathode surfaces.
4. presence of the corrosion damages on the passive surface and on the passive-carbon one indicates that it is impossible to orient the current passage through the bone screw's passive zone, located in the compact bone region. The volume of the anode mass losses caused by stimulation with the direct current is in accordance with the Faraday's law. Any eventual corrosion damages on cathodes' surfaces can be defined as local etchings.
5. overcolourings observed in the compact bone region are the effect of the corrosion products' infiltration from anode. The maximum atomic concentrations of the chemical elements reach: Cr - 23.65%, Fe - 17.07%, Mo - 3.5%, Ni - 2.1%. The bone tissue infiltration region by the corrosion products in the direction of the current passage is 7 mm, whereas it is 11 mm in the opposite direction. The corrosion defects on the anode's surface and corrosion products from anode in the bone tissue indicate that employing this stimulation method to activation of the fractured bone union with the direct current, is very disadvantageous and may lead to serious reactive complications

REFERENCES

1. Forsted D. L., *et al.* Radiology, 1978, 128, 629-634.
2. Kostrzewski K., *et al.*, Chirurgia Narządu Ruchu Ortopedia Polska, 1979, 2, 121-124.
3. Connoly J. F., *et al.* Ann. N. Y. Acad. Sci., 1974, 238, 519-525.
4. Weigert M., *et al.* Zbl. Chirurgie, 1978, 103, 1945-1948.
5. Cieszyński T., Chirurgia Narządu Ruchu Ortopedia Polska, 1970, 4, 507-511.
6. Goodman E., *et al* 8th Annual Meeting of the Bioelectrical Repair and Growth Society, Washington, 1988.
7. Szewczenko J., *et al.* Engineering of Biomaterials, 1999 7,8, 21-26.
8. Marciniak J., Reasearch project of the Polish State Committee for Scientific Research (KBN) 4 1738 91 01, Silesian University of Technology, Gliwice 1991/94.