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FRACTOGRAPHIC INVESTIGATION OF FAILURE IN STAINLESS STEEL ORTHOPEDIC PLATES

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Abstract. *Plates of austenitic stainless steel are often used in orthopedic surgery for fixing ends of the broken bones and for repairing fractures. The paper analyzes a premature breakage of six plates for fixing broken bones with different patients during their recovery. Each plate's breakage can induce serious aftermaths such as a new surgery, unexpected undesired complications and a prolonged healing time. The research of the plate breakage required an examination of the chemical composition and steel hardness, metallographic examination as well as that of the plate breakage surface by means of macroscopic and microscopic fractographic observations using stereomicroscope and scanning electron microscope. On the basis of the results it can be concluded that the breakage was caused by steel wear with a high static load and with no corrosion.*

Key words: *Austenitic Stainless Steel, Bone Fixture Plate, Breakage Cause Analysis, Breakage Surface Analysis*

1. INTRODUCTION

The biomaterials can be used in the human body when it comes to the cases of repairing and replacing damaged body parts, of improving and healing injuries and of modifying dissonant and unnatural situations of different parts of the human body. Metallic biomaterials are widely used for repairing broken or cracked bones. The reason for this is their ability to appropriately carry loads applied to the bones. These materials are divided into two groups of prosthesis and bone healing fixation equipments, according to their functionality time in the body. Prostheses are designed for long-term applications in the body of patient while the other group is merely used for keeping the bone in shape in a temporary period of bone reconstruction and is to be removed from body after the healing period completion [1].

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Various alloys including stainless steel, titanium alloys, cobalt-chromium alloys and shape memory alloys are used for fabrication of orthopedic implants [2]. Nowadays, austenitic stainless steel is one of the most important materials for fracture fixation devices compared to the other mentioned alloys, due to its very good combination of mechanical properties, corrosion resistance and appropriate price [3].

Stainless steel is widely used for temporary orthopedic implants such as bone screws, plates and implanted medical devices, besides surgical instruments [4]. These materials have high corrosion resistance as they spontaneously form oxides on the surface in various environments. Other advantages, such as its good mechanical properties and low cost, make stainless steel one of the most appropriate biomaterials for surgical implants. These properties, along with biocompatibility, recommend these materials as biomaterials since we should always bear in mind that body fluids are oxygenate saline solutions containing chloride ions, and are, therefore, highly corrosive. Orthopedic implants are often subject to mechanical stress and wear. Hence, the implant materials should have adequate strength, flexibility, and wear resistance.

Regarding a variety of fractures in patients, various kinds of plates for bone healing, screws and pins of different dimensions have been designed and used. These plates get fixed to the broken bones by means of screws after the broken fragments are joined; they are designed in such a way that maintaining the bone in its original shape and applying compression stress will help to foster fast healing of the broken bone. Compression loads are transferred through plates until the complete healing of broken bone is achieved [5].

The reason of an implant failure may result from mechanical overload, under static or dynamic load, mutual action mechanical and corrosion attack and mechanical effect of calcification of bone during the accretion. Orthopedic implants' exposure to the biomechanical and biochemical influences and interactions between the implants and the biological environment may lead to failure due to mechanical or biomechanical reasons [6]. Direct overloading, fatigue or corrosion fatigue damage is one of the major reasons for failure of austenitic stainless steel screws and plates. Various types of forces act on the implants and the bones producing the stresses, which lead to failure, in certain time interval.

In the intact musculoskeletal system, the acting forces are balanced. When a bone is fractured, the balance of forces is destroyed, and the muscle forces pull the bone fragments in various directions. During operative reconstruction of a fractured bone, attaching the fragments to orthopedic implants stabilizes the fracture. If the bone is perfectly reduced, the entire implant is supported by the bone, the acting forces are again in equilibrium, and only relatively small and uncritical loads are exerted on the implant. However, if the bone is not perfectly reconstructed, if fracture gaps are present or fragments of bone are missing, the weight-bearing forces are not completely balanced and the loads may be unevenly distributed. As a result, bending and torsion stresses can concentrate on exactly those areas of the implant where the bone support is missing. The implant undergoes cyclic loading in these zones and the risk of fatigue damage increases. It is not necessary for the implant to be loaded in the plastic deformation range for fatigue cracks appearing. Local stress concentrations may be sufficient to initiate fatigue cracks on the surface of the implant. The progress of fatigue damage depends on the number of load cycles, intensity and kind of loading, as well as the state of applied steel. Finally, when cross section is sufficiently reduced static fracture occurs. On the fracture surface we can clearly distinguish both the zone of fatigue damage and the static fracture zone also known as a fast fracture region. In the case of high stress, the fast fracture region is predominant to the fatigue damage zone, often with presence of slip lines.

Fracture of orthopedic plates before the bone repair period completion, results in serious accidents like need for repeated surgery, complexities and extension of healing period and also increasing of remedy expense. Plates implanted in body may fracture in a simple or complex manner depending on the loading condition. Several mechanisms have been reported in referential literature on fracture of orthopedic plates, ranging from overloading, stress assisted corrosion, fretting, low stress fatigue, unidirectional bending to ductile fracture assisted by non-metallic inclusions [7-10]. Various kinds of stresses appearing in an implant in the body involve compression, tension, torsion, shear, bending and any combination of them while the installation technique significantly affects the stresses suffered by plate. The each identification of mechanisms in the fracture process of these plates would be very useful for optimum use of them and improvement of their efficiency.

2. Experimental methods

2.1. Samples data

Several plates that failed inside of patients and were removed during second surgery for the replacement of the implants were supplied for failure investigation. Their history is unknown. There were more than six fractured plates, but these ones were separated for analyzing. The plates are provided by the staff of University Traumatology Clinic, Faculty of Medicine University of Niš.

The orthopedic plates with suitably prepared holes were mounted by means of screws to the bones. They contain holes with countersinks. Diameter of holes is 4.5 mm, with a wider conic area. The condition of the surface of the plate was smooth, without corrosion artifacts and no signs of accidental damage. Appearance of the failed plates is shown in Fig. 1. Dimensions of the cross section areas of the plates are shown in Table 1.

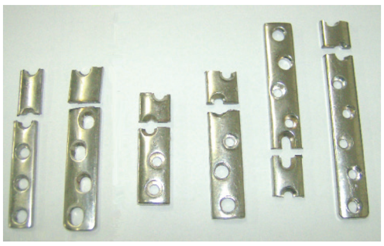

Fig. 1 Six investigated plates with cut parts for SEM analysis of failure surface

Table 1 Cross section areas of the plates

Plate number	1	2	3	4	5	6
Width (mm)	12.5	16.5	16.0	16.5	15.5	15.8
Thickness (mm)	3.8	4.5	6.0	4.5	4.5	4.5

All the six plates are similar in their chemical composition and surface hardness. Accordingly, only one plate is elected to show chemical composition and metallorgaphy.

2.2. Applied method

Chemical composition of the plate was determined by the spectrometer chemical analyzer. Specimen preparation for micro-structural observation was carried out by means of standard metallography techniques, followed by etching the polished surface into solution consisting of 2 g picric acid, 10 ml hydrochloric acid and 100 ml ethanol. Micro-structural observation was conducted on the section parallel to the fracture surface plate with the use of the stereomicroscope. Macro-hardness measurements were performed by using the Rockwell B hardness testing method. The failed plates were subjected to ultrasonic cleaning in ethanol prior to fractographic examinations. Macroscopic and microscopic studies of the fracture surfaces were conducted by using scanning electron microscope (SEM) JEOL JSM 5300.

3. Results and Discussion

3.1. Chemical analysis and metallography

The results of chemical analysis are shown in Table 2 which are in good agreement with the standard chemical composition for 316L austenitic stainless steel [11].

Table 2 Chemical composition of plate 3

All in (wt. %)	Chemical composition					
	C	Cr	Ni	Mo	Mn	3.3(%Mo) + %Cr
Plate 3	0.029	17.60	15.25	2.38	1.50	**25.45**
ISO 5832-D	max 0.03	17-19	13–15	2.25–3.50	max 2.00	min 26
ISO 5832-E	max 0.03	17-19	14–16	2.25–4.20	max 2.00	min 26

Representative optical micrograph for tested steel is shown in Fig. 2. It can be seen that their microstructure comprises a single phase matrix consisting of average grains size of austenite with a certain number of non-metallic inclusions (NMI) and pores (P).

3.2. Hardness measurements

The hardness of the plates was measured by using the Rockwell B method (sphere indenter made of hardened steel, diameter 1.588 mm, load 981 N). Results of the measurements are given in Table 3 as well as present average values of six measurements on both sides of same plate. For the case of comparing the last row in the Table presents macro hardness converted to Vickers units. The hardness of the plates was found to be fairly uniform along surface of the plate. Also, the average hardness of the implants was very uniform; it varies from 97 to 102 HRB.

Table 3 Average hardness of tested plates

Plate number	1	2	3	4	5	6
HRB	99	102	98	97	100	102
HV	242	268	234	228	250	268

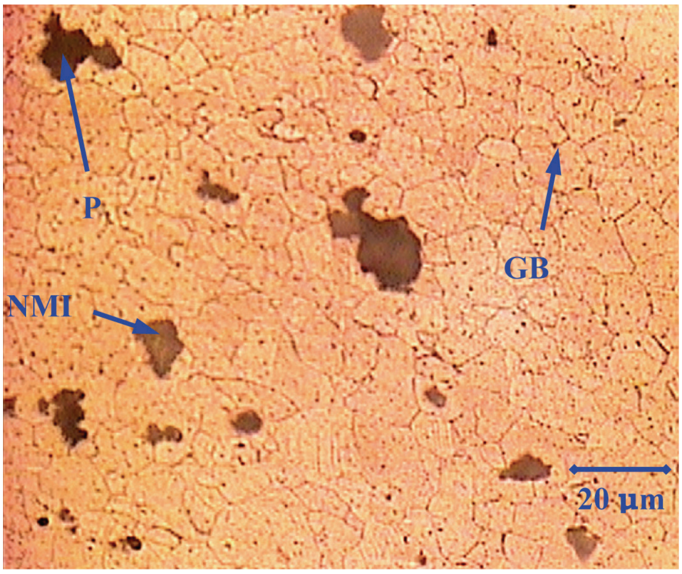

Fig. 2 Optical micrograph of transverse section of plate 3, GB – grain boundary, NMI – non-metallic inclusion, P - pore

3.3. Macroscopic analysis of fracture surfaces

Orthopedic plates are subjected to a combination of static and cyclic loads in the body [7, 12]. The cyclic component of the load varies with position in the normal walking cycle and reaches a peak of about four times the body weight at the hip and three times the body weight at the knee [7]. Fractographic studies showed that the cyclic component of the sustained loads activated the fatigue fracture process [13]. There are three typical fatigue stages including crack initiation, crack growth and the final fracture in theory of fracture mechanics.

It can be seen from the failed plates, shown in Fig. 1, the fractures locations were at a section passing through a hole on the plate where the cross sectional areas are minimal and the internal stresses are maximal. The general orientation of the fracture surfaces is roughly perpendicular to the longitudinal axis of the plates. In case of prior damage of plate surface (scratch, large non-metallic inclusion) initial crack can start and propagate through plane angled different from perpendicular to longitudinal axis. Macroscopic appearance of the fracture surfaces indicates that the fracture process occurred without any significant change in the cross section of plate and no plastic deformation nearly to fracture. Accordingly, the fracture process of the plates can be categorized as a macroscopically the most brittle fatigue.

Visual examinations of the fracture surfaces of the plates suggest the complete absence of corrosion contribution to the failure process (see Figs. 3-5). The presence of narrow flat areas along the ledge can be seen in the given Figs. The narrow area can be seen clearly in Fig. 4 but it is noticed for all other samples. The presence of narrow zones along the edge of plates with relatively smooth surface points to fatigue initiation in all the six plates. The crack origin is not possible to determine exactly in these cases because the zone is elongated and of relatively uniform width. Accordingly, there are no slip lines to indicate the direction of the propagation on the crack.

The rest of the fracture surface consists of the relief surface indicating to static mostly brittle fracture, caused by a relatively high stress. Moreover, this surface contents damages due to metallurgical defects (non-metallic inclusions, pores, etc., Figs. 3, 4) and damage due to mechanical actions of mating fractured parts (see Fig. 5).

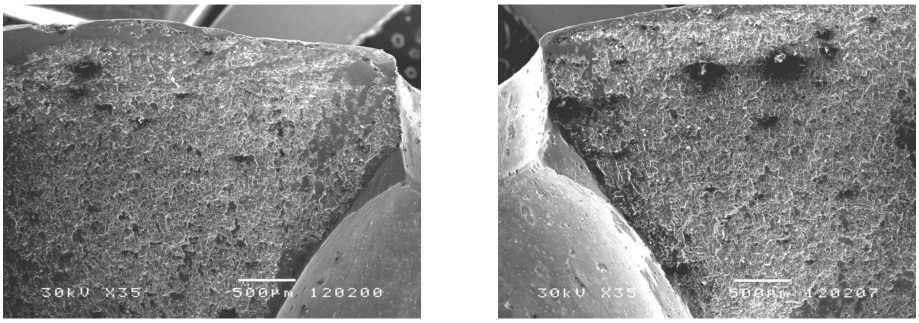

Fig. 3 SEM macrograph of fracture surface plate 1

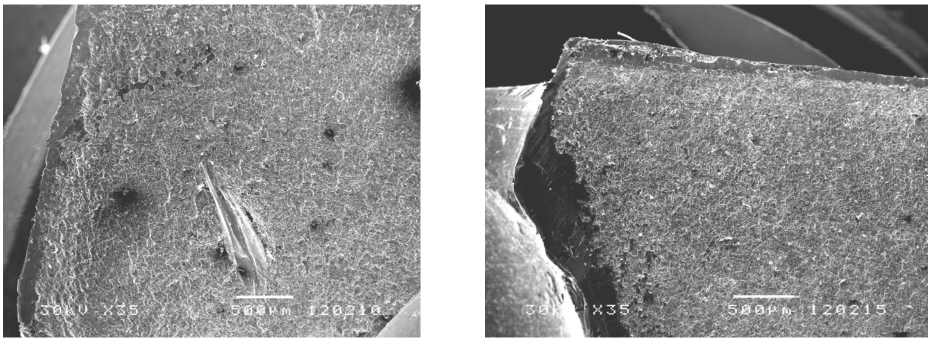

Fig. 4 SEM macrograph of fracture surface plate 2

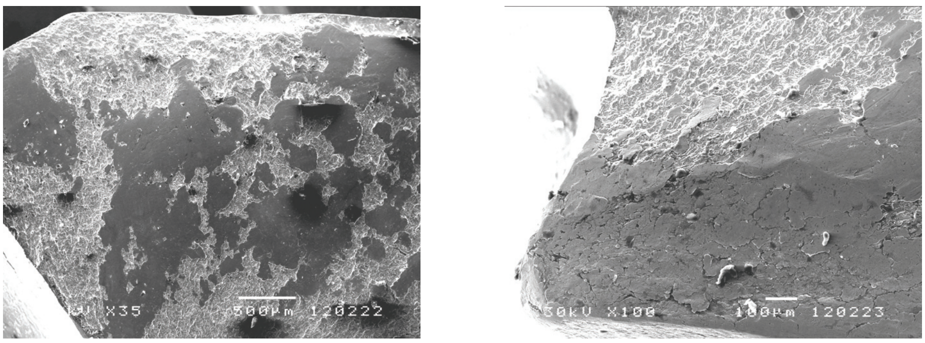

Fig. 5 SEM macrograph of fracture surface plate 5

3.4. Microscopic analysis of fracture surfaces

Fast fracture region of one plate is uniform considering type of fracture. A slight difference between types of static fracture can be seen for all the plates. There is a mostly brittle fracture (see Fig. 6) and brittle with element of ductile fracture (see Fig. 7).

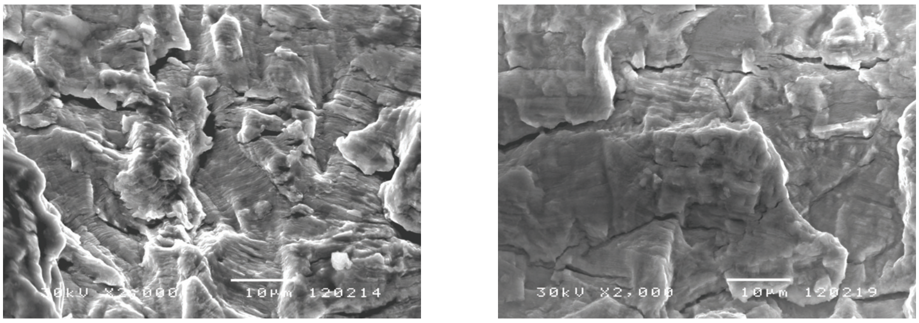

Fig. 6 SEM micrograph of fast fatigue region of plate 2

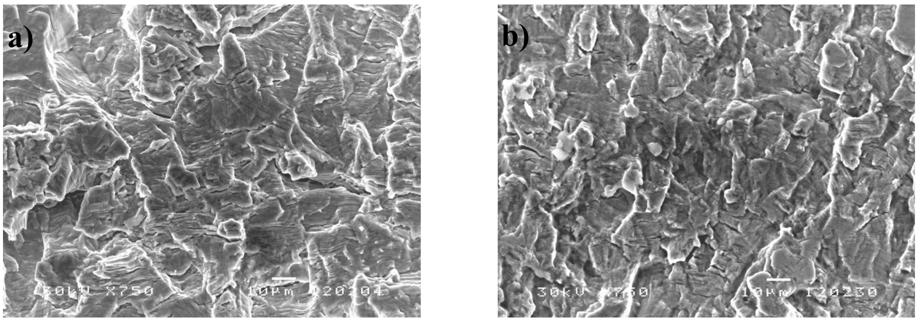

Fig. 7 SEM micrograph of fast fatigue region of: a) plate 1 and b) plate 5

4. CONCLUSIONS

On the basis of all previous described methods of the investigation and obtained results, the following conclusions can be drawn:

- There is no corrosion activity on the fracture surfaces.
- The fatigue was the main reason of plate failure.
- Failures are mainly provoked by bending loads.
- The initial crack probably occurred somewhere in size hole on the plate
- Crack initiation can be provoked by surface irregularity as scratch, pore, local plastic deformation etc. or metallurgical defect near to surface.
- There is a narrow zone along the edge of plates with relatively smooth surface pointing to fatigue presence, in all six fracture surfaces.
- Rest of fracture surface consists of the relief surface indicating to static mostly brittle fracture, caused by relatively high stress.

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FRAKTOGRAFSKO ISPITIVANJE LOMA ORTOPEDSKIH PLOČICA OD NERĐAJUĆEG ČELIKA

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Pločice od austenitnog nerđajućeg čelika često se koriste za učvrćšivanje krajeva polomljenih kostiju i saniranje preloma u ortopedskoj hirurgiji. U radu je analiziran prevremeni lom šest pločica za fiksaciju polomljenih kostiju kod različitih pacijenata. Svaki lom pločice može prouzrokovati ozbiljne posledice, kao što su: nova operacija, neočekivane neželjene komplikacije i produženi period ozdravljenja. U cilju istraživanja loma pločica, izvedeno je ispitivanje hemijskog sastava i tvrdoće čelika, metalografsko ispitivanje, kao i makro i mikro fraktografsko ispitivanje površine loma pločica, pomoću optičkog i elektronskog mikroskopa. Na osnovu rezultata ispitivanja može se zaključiti da je lom nastao usled zamora čelika sa visokim statičkim opterećenjem, bez prisustva korozije.

Ključne reči: *austenitni nerđajući čelik, pločica za fiksaciju kosti, analiza uzroka loma, analiza površine loma*