FRACTOGRAPHIC INVESTIGATION OF FAILURES IN 316L STAINLESS STEEL ORTHOPEDIC CONDYLAR BLADE PLATE

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ABSTRACT

In this paper, premature fracture of two condylar blade plates that failed inside the thigh of two separate patients is investigated. Condylar blade plates made of 316L austenitic stainless steel are widely used for internal fixation and repair of femoral fractures in orthopedic surgery. Fracture of such plates could have serious consequences such as the need for repeated surgery, extra unwanted complications and extension of the healing period. In addition to selecting the proper plate for fixation, the fixation technique has significant influence on the forces applied to the plate and affects the healing process. The failure investigation mainly included chemical analysis, metallography, hardness testing, as well as macroscopic and microscopic fractographic observations using stereomicroscope and scanning electron microscope, respectively. Based on the results of fractographic studies, fatigue fracture mechanism was identified as the primary cause of failure. Fatigue crack initiation was found to take place at relatively sharp corners around the designed central holes on the condylar blade plates, which acted as stress raisers on the reduced cross sections. Since prior to healing, the loads are primarily transferred through the plates, proper post-operative immobilization can be effective in preventing fatigue failure of the plates.

Keywords: 316 L stainless steel, Condylar blade plate, Fatigue, Fractography.

1. INTRODUCTION

Biomaterials are used in human body in case of curing, replacement of damaged members, improving and healing injuries and modification of dissonant and unnatural situations of different parts of the human body. Metallic biomaterials are widely used for healing of defected bones. This is because they can appropriately carry tension 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 body. Prosthesis are designed for long-term applications in the body of patient while the other group are merely used to keep the bone in shape in the temporary period of bone reconstruction and are removed from body after complement of curing period [1].
According to variety of fractures in patients, various kinds of plates for bone healing, screws and pins of different dimensions have been designed and used. Orthopedic 95° Condylar Blade Plates are series of plates which are useful in repair of metaphysical fractures primarily

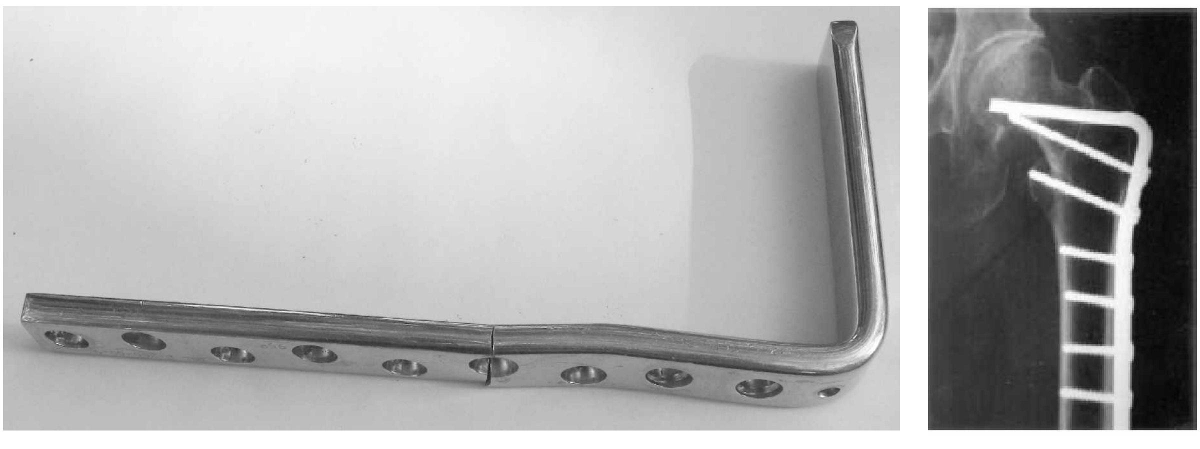
of the femur and may be used as compression plates with the external tensioning devices. These plates are fixed on broken bones by means of screws after placing the broken fragments and have been designed in a way that by maintaining the bone in its original shape and applying compression stress will help to correct fast healing of the broken bone. Compression loads are transferred through plates until reaching complete healing of broken bone [2].

Various materials including stainless steel, titanium alloys, Co-Cr alloys and shape memory alloys are used in fabrication of orthopedic implants and bone plates. Nowadays, 316L austenitic stainless steel is one of the most important materials for fracture fixation devices compared to the other mentioned alloys, due to its excellent mechanical properties, corrosion resistance and appropriate price [3].

Fracture of orthopedic plates before completion of remedy period 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, related to loading condition. Several mechanisms have been reported in literature on catastrophic fracture of compressive orthopedic plates, ranging from stress assisted corrosion, fretting, low stress fatigue, unidirectional bending to ductile fracture assisted by non-metallic inclusions. Various kinds of stresses are applied to an implant in body involve axial compression, axial tension, torsion, shear, bending and any combination of them and installation technique significantly affects the stresses suffered by plate [4]. Identification of active mechanisms in the fracture process of these components would be very useful in presenting appropriate method for optimum use of them and improvement of their efficiency [5-7]. In the present study, two fractured condylar plates removed from patients by repeated surgery were investigated to determine the reasons of their fracture during remedy period in patient body.

2. EXPERIMENTAL METHODS

Two 95° condylar blade plates that failed inside the thigh of two patients and were removed during second surgery for the replacement of the device were supplied for failure investigation. The orthopedic plates with suitably prepared holes were mounted by means of screws to the femur bone. One of the failed plates along with a radiographic image of the plate-screw-bone structure is shown in Figure 1. The dimensions of the long axis of the plate are 173×15×6 mm. The plate contains a total of nine central holes on the long axis.



(a) (b)

Figure 1. (a) Photograph of one of the failed condylar blade plates under investigation and (b) Radiographic image of the plate-screw-bone structure in the body [8].

The failed plates were subjected to ultrasonic cleaning in acetone and ethanol prior to fractographic examinations. Following visual examinations, digital camera photo documentation and stereomicroscope observations, microfractographic studies of the fracture surfaces were conducted using scanning electron microscope, equipped with EDS analysis facility.
Specimen preparation for microstructural observations was carried out using standard metallography techniques, followed by etching the specimens with a solution consisting of 6 parts HCl and 4 parts HNO_3. Microstructural observations were conducted on sections parallel to the fracture surfaces of condylar blade plates using optical and scanning electron microscopes. Macrohardness measurements were performed using Vickers hardness testing method at a load of 30 kgf.

3. RESULTS AND DISCUSSION

3.1 Metallography and chemical analysis

Representative SEM micrograph showing the microstructure of a failed condylar blade plate is shown in Figure 2. It can be seen that the microstructure exhibits a single phase matrix consisting of relatively coarse grains of austenite. Some slip lines and twins can be observed in some of the grains. The average hardness number of the condylar blade plates was found to be 310 VHN, which was fairly uniform across various metallographic sections.

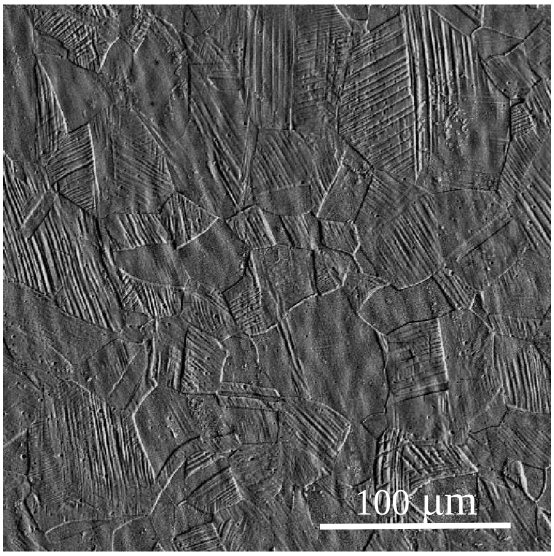


Figure 2. SEM micrograph showing the microstructure of a failed condylar blade plate.

Chemical analysis was conducted using energy dispersive spectroscopy method. The results of chemical analysis are shown in Table 1, which are in good agreement with the standard chemical composition for 316L austenitic stainless steel [1].

Table 1. Chemical composition of a failed condylar blade plate

Source of data	Composition (wt. %)				
	Cr	Ni	Mn	Mo	Fe
Chemical analysis	18.6	13.6	1.7	2.3	balance
316L [1]	17-20	12-14	<2	2-4	balance

3.2 Macroscopic fracture surface

It can be seen from the failed condylar blade plate shown in Figure 1 that the fracture location was at a section passing through a central hole on the plate where the cross sectional area is minimal. The general orientation of the fracture surface is roughly perpendicular to the long axis of the plate. Macroscopic appearance of the fractured condylar blade plate indicates that the fracture process occurred without any measurable change in cross sectional area or plastic deformation. Accordingly, the fracture process of the plates can be categorized as a macroscopically brittle fracture process [9,10]. Furthermore, visual examinations of the surface finish of the devices suggest the complete absence of corrosion contribution to the failure process. The fracture surfaces of the condylar blade plates under investigation are shown in Figure 3. The position of the fracture plane with respect to the central hole at fracture location can be clearly observed in this figure.

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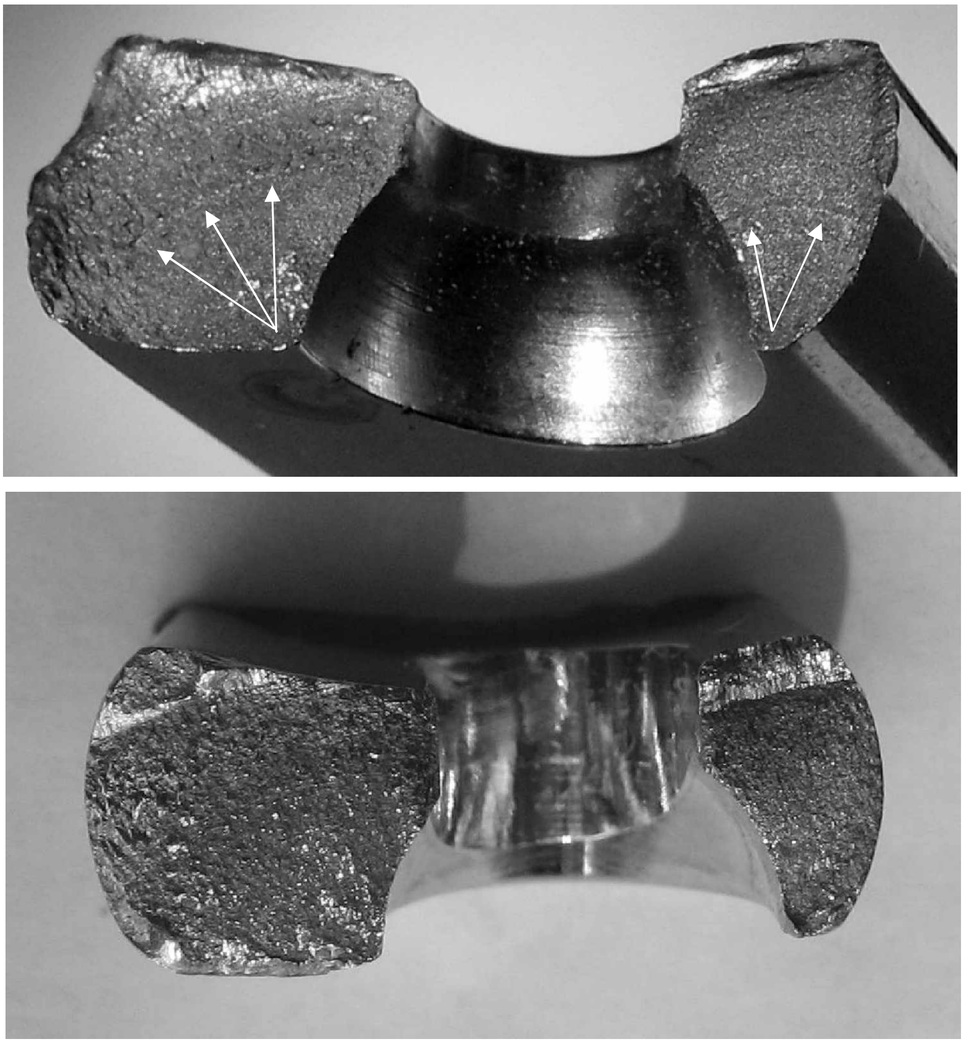

Figure 3. Fracture surfaces of the blade plates (×7).

Parallel and concentric bands of beach markings can be identified in localized regions near the middle part of the fracture surfaces as shown in Figure 3. Presence of beach markings in the macroscopic scale is indicative of the progressive nature of crack growth under variable amplitude fatigue loading conditions, with each marking delineating the position of the crack front at different stress amplitude [10].

Considering the orientation of the curved beach markings, crack initiation region can be traced back to the relatively sharp edged corners at the surface of designed central holes on the condylar blade plates, as shown by the superposed arrows in Figure 3. These regions acted as stress concentration sites on the reduced cross sectional area caused by the presence of central holes. A low magnification SEM fractograph showing the fracture surface of one of the blade plates is presented in Figure 4.

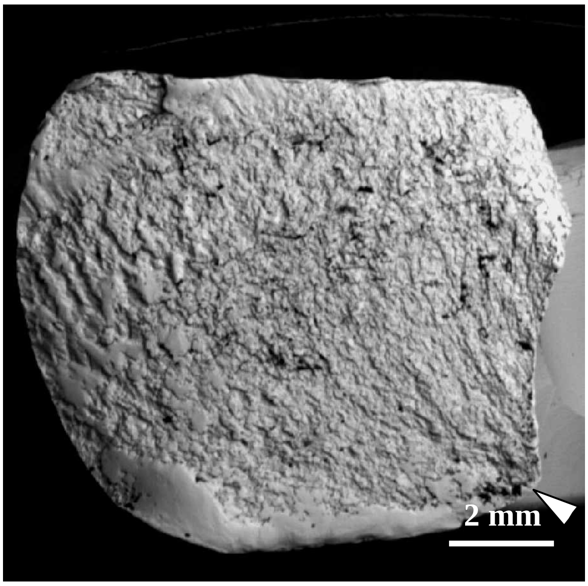

Figure 4. SEM fractograph showing the fracture surface. The arrow points to the crack initiation region.

Radial lines originating from the crack initiation region in the general macroscopic crack growth direction and some faint beach markings can be identified on the fracture surface. The crack initiation region is shown at higher magnification in Figure 5.

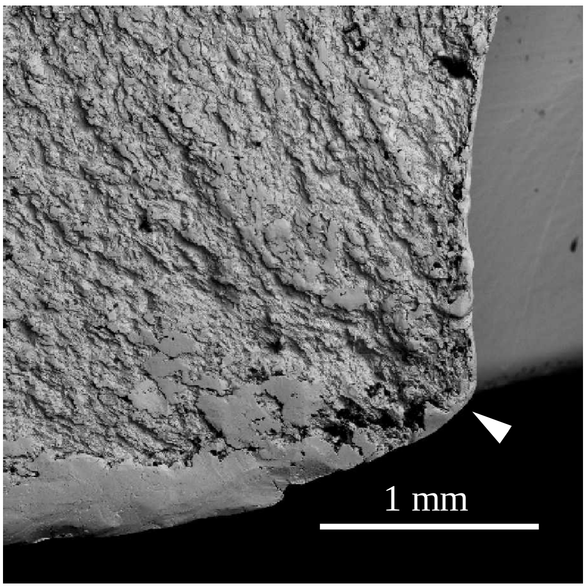

Figure 5. Higher magnification SEM fractograph of the crack initiation region at the corner of a central hole on the condylar blade plate.

3.2 Microscopic fracture mechanisms

It can be seen in the above fractographs that repeated contact of the mating fracture surfaces during the failure process and/or a post-fractural abrasive motion of the screw located at the fracture site has seriously damaged the fracture surface and obliterated many of its features. However, fractographic examinations of undamaged regions in between the macroscopic beach markings at higher magnifications reveals the formation of fine and dense striations as shown in Figure 6.

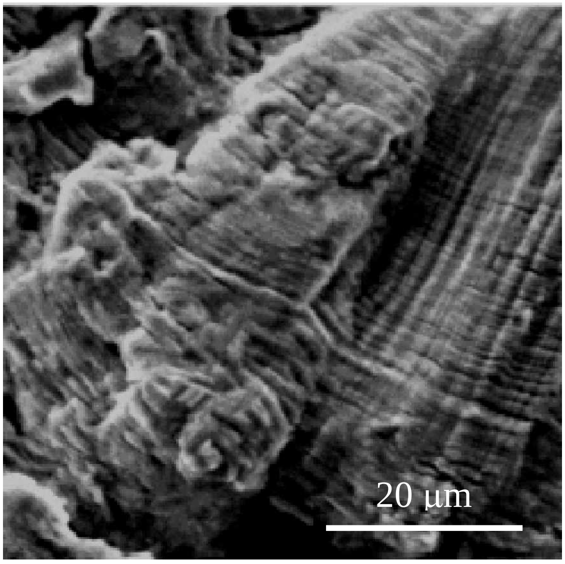

Figure 6. SEM fractograph showing typical striations on the fatigue fracture surface.

Striations, which show the position of crack front during successive loading cycles, are considered as the main microscopic sign of failure by fatigue fracture process [9,10]. Subcritical stable fatigue crack growth by striation formation continued until the onset of final fracture. The fast fracture region exhibits a dimpled morphology (Figure 7) characteristic of failure by ductile rupture mechanism [10].

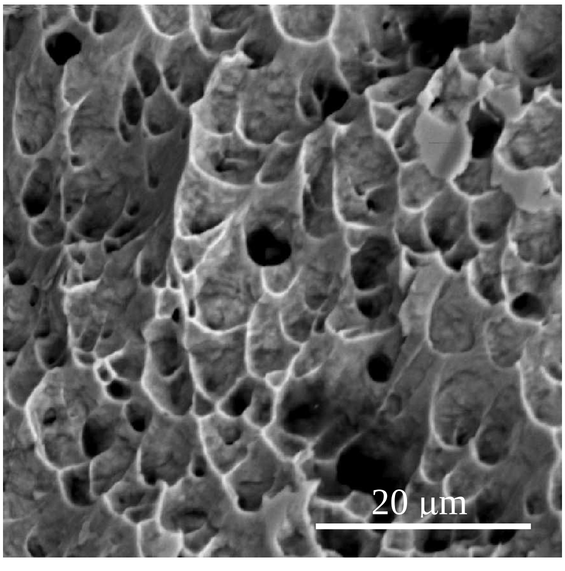

Figure 7. SEM micrograph of dimples formed in association with nonmetallic inclusions in the final fracture region of the condylar blade plate.

Initiation of voids in the dimpled fast fracture regions was facilitated by the presence of nonmetallic inclusions. Clear Shear lips formed at the ends of the final fracture regions can be seen on the fracture surfaces shown in Figure 3.

The above findings indicate that failure of condylar blade plates can be mainly attributed to mechanical causes. These orthopedic implants are subjected to a combination of static and cyclic loads in the body [4,11]. 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 [4]. Fractographic studies showed that the cyclic component of the sustained loads activated the fatigue fracture process. The three typical fatigue stages including, crack initiation, crack growth and the final fracture were identified on the failure surfaces of condylar blade plates. Fatigue cracks initiated at relatively sharp corners of central holes on the plates and progressively advanced by striation formation until the maximum load on the remaining cross section exceeded the load carrying capacity of the material.

Since the main intent of using a fixation device is to hold the ends of the broken bones in close proximity to promote the healing process, it is clear that the plates sustain most of the imposed loads until substantial healing of the bone. Furthermore, the tensile strength, the fatigue strength and the elastic modulus of the bone is approximately ten times less than the cold worked stainless steel [4]. Thus the fixation screws responsible for fastening the blade plate on the bone may easily loosen, if sufficient time for significant development of the bone tissue surrounding the fracture is not allowed. Consequently, premature walking motion of the patient can lead to loosening of the implant fixation and the application of the above mentioned cyclic loads solely on the fixation device. This, in turn, can produce periodic local stress cycles, which are further intensified at stress concentration sites, leading to fatigue failure of these implants.

4. CONCLUSIONS

1- The three typical fatigue stages including, crack initiation, crack growth and the final fracture were identified on the failure surfaces of condylar blade plates.

2- Fatigue crack initiation occurred preferentially at the relatively sharp corners of central holes on the orthopedic plates.

3- Stable cyclic crack growth occurred by a striation formation mechanism. Dense bands of macroscopic beach markings suggested that the imposed cyclic loads were applied under variable amplitude conditions.

4- The fast fracture region exhibited a dimpled morphology indicative of final failure by ductile rupture mechanism.

5- Since prior to sufficient healing of the bone, the loads are primarily transferred through the support plates; proper post-operative immobilization can be effective in preventing the application of cyclic loads and avoiding fatigue failure of condylar blade plate implants.

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