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Failure analysis in 316L stainless steel supracondylar blade plate☆

L. Guerra-Fuentes, E. Garcia-Sanchez, A. Juarez-Hernandez, M.A.L. Hernandez-Rodriguez *

Universidad Autónoma de Nuevo León, Facultad de Ingeniería Mecánica y Eléctrica, San Nicolás de los Garza, N.L., Mexico

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ABSTRACT

A 316L stainless steel blade plate implant used for fixation of a femoral fracture in a female patient failed catastrophically at four months of service. The failure examination included visual inspection, chemical analysis, metallography, hardness testing, as well as macroscopic observations using scanning electron microscope with EDS (energy-dispersive X-ray spectroscopy). The visual inspection and X-ray radiography images exhibited that there was heterogeneous bone callus formation and the fixation screws showed surface damage by fretting wear. On the other hand, SEM results showed evidence of fatigue based on the characteristics of the fracture surfaces. It was observed that the particular high curvature femur of the patient resulted in high tensile stress between bone and screws threads. It promoted rapid losing of primary fixation and subsequently generated a high stress concentration in the plate at cantilever which resulted in premature failure by fatigue.

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 are biocompatible and they can appropriately carry tension loads applied to the bones [1].

An orthopedic implant is an artificial mechanical device that replaces or supports part of the skeletal structure of the human body. One of the applications includes internal fixation of fractures by bone plates, nails or intramedullary rods [2].

Metallic implants materials made of stainless steel have been found to have many applications as medical devices [3–6]. Nowadays, 316L austenitic stainless steel is one of the most used materials for fracture fixation devices compared to the other mentioned alloys, due to its suitable mechanical properties and low cost [7].

However, several failures in orthopedic implants have been reported due to mechanical failure including plastic and brittle fracture, corrosion pitting and fatigue. Some of these failure mechanisms have been related to poor design or lack of quality in metallurgical process [8,9].

In treating distal femur fractures, it can be difficult to maintain bony alignment; in 1967 Neer recommended a nonsurgical approach to supracondylar fractures after reviewing 110 unselected cases, noting a high rate of local complications and a low rate for patient satisfaction [10,11]. Nowadays fixation with a lateral condylar blade plate or its modifications became popular treatment because it allowed fixation of intra-articular fractures and early mobilization of the knee joint [12–14].

This work investigates a fractured supracondylar plate removed from a 53 year old female patient, who presented a fracture revision after four months of service before callus formation had occurred.

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* Corresponding author.
E-mail address: malhdz@gmail.com (M.A.L. Hernandez-Rodriguez).

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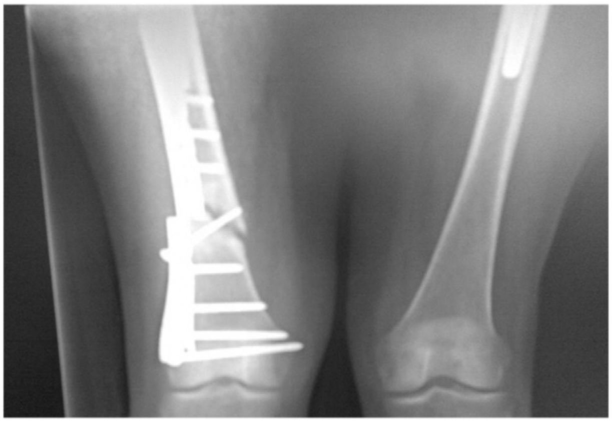

Fig. 1. X-ray image showing the bone and the failed supracondylar plate.

2. Experimental procedure

Fig. 1 shows an X-ray radiograph of the fracture where the two screws that stabilize the small third fragment are inserted in lag screw fashion and compress the fracture gaps of the femur near to the knee joint along with the supracondylar blade plate.

The failure of the supracondylar blade plate is shown in Fig. 2. The plate was cleaned carefully using a solution of ethanol and methanol using an ultrasonic cleaner. Different sections were selected and sectioned: "A", "B", "C" and "D" regions were prepared for fractographic and metallographic inspection (Fig. 2). Sections "A" and "B" correspond to the fracture area which was analyzed using a FEI Nova NanoSEM 200 with a voltage of 20 kV. In order to analyze the topography of the fracture, it was used in secondary electron mode and backscattered electrons to analyze impurities present in the failure. Sections "C" and "D" were used to analyze the microstructure; for this purpose these sections were metallographically prepared and chemically etched using a saturated solution of 2% ferric chloride in 98% of HCl by immersion; additionally chemical composition was obtained using atomic absorption spectroscopy.

3. Results and discussion

Fig. 3 shows the microstructure of the supracondylar blade plate; a typical austenitic 316L microstructure with twins in some grains which correspond to the pre-deformation of the material during its processing can be observed. Twinning is generally considered as a deformation mechanism that is activated at high strain rates [15–18]. The average microhardness is 320 HV; this value is in agreement with others reported in similar plates [2,19].

The results of chemical analysis are shown in Table 1, which are in good agreement with the Standard ASTM F138-00 for implant materials "Standard Specification for Wrought 18 Chromium–14 Nickel–2.5 Molybdenum Stainless Steel Bar and Wire for Surgical Implant (UNS S31673)" [20].

SEM representative image of section "A" is shown in Fig. 4. This image presents the fracture surface of the failed supracondylar plate. In this surface at least two regions are evident, one of them are rough zones distributed in the fracture surface; these regions are associated with striations, the other region corresponds with flat and more white zones; these "flat" zones observed in the fracture surface were related to fracture surfaces damaged by cyclic contact in the first stage of cracking previous to the complete separation of the plate.

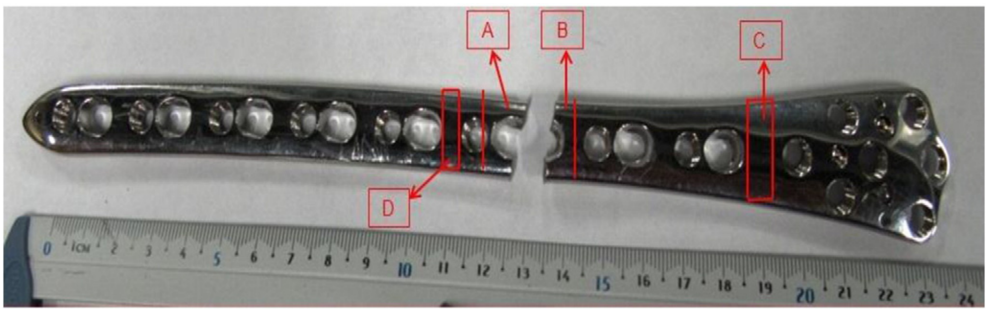

Fig. 2. Supracondylar plate showing the transversal fracture through one of the holes. Sections A, B, C and D were used to the chemical and metallographic material characterization and fractographic analysis.

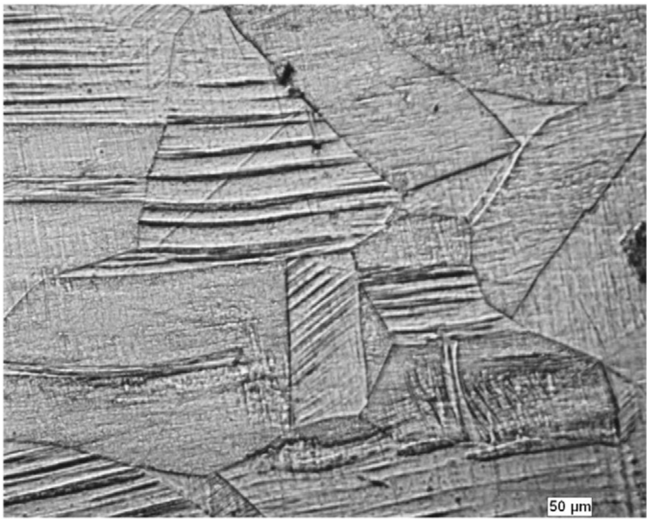

Fig. 3. Micrograph of section "D" with etching.

Table 1
Elemental composition of a condylar blade plate.

	Cr	Ni	Si	S	Mn	Mo	C	Fe
Plate	17.45	14.18	0.47	<0.01	1.82	2.81	0.015	Bal.
ASTM F-138-00	17–19	13–15	0.75 max.	0.001 max.	2 max.	2.25–3	0.03 max.	Bal.

The point of crack initiation is not clearly observed; however it is possible to see a line of crack propagation. Fig. 4 in backscattered electrons provides contrast based on chemical composition and there is no evidence of inclusions or corrosion artifacts in the fracture zone.

The results of the fractographic analysis indicated that the fracture morphology from the supracondylar plate corresponds with a common fatigue and finally cleavage decohesion mode of fracture (Fig. 5). This mode of fracture could be associated with fretting and mechanical fatigue under low stresses; fatigue striations are observed in the surface in the same direction that the crack was presented. According to Fig. 1 the compression plate could be working at least under unidirectional bending although it is known that the stress state during service could be more complex including combined compression, torsion, flexion, or bending and this condition promotes this mode of failure.

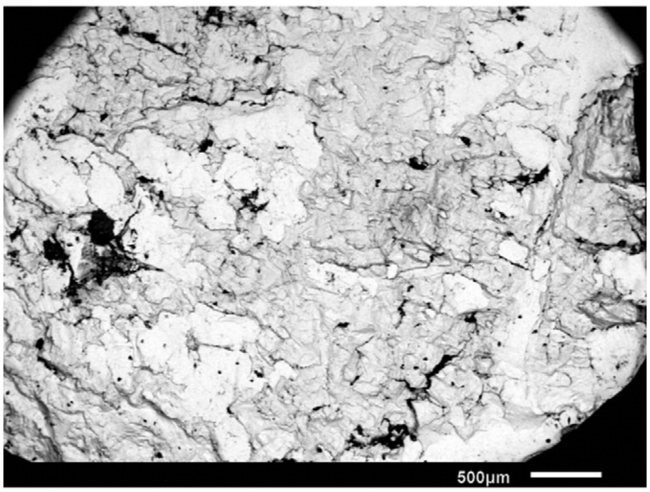

Fig. 4. Backscattered electron SEM image showing the fracture surface details.

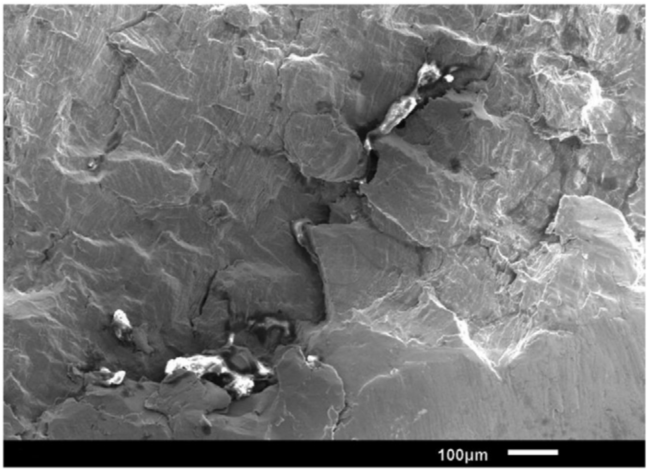

Fig. 5. Secondary electron SEM image of the fracture surface.

The fixation screws responsible for fastening the compression plate on the bone may easily loosen, if it has not allowed for sufficient time so that significant development of the bone tissue surrounding the fracture to occur [21]. In this case and according to the observations in the X-ray image (Fig. 1), because of the curvature of the bone the plate was not anatomically fitted to the bone. Upon placing the plate screws in the bone these were fixed with an initial tension state, promoting fatigue by the natural movement of the patient and the well known difference of mechanical properties between the steel and bone caused a quick release and a concentration of stresses; these efforts were higher than conventional because the position of the plate and the quality of the bone, based on Fig. 1, increased the propagation rate of crack and subsequent failure.

Fig. 5 shows artifacts in the crack zone; these were analyzed by EDS (Fig. 6(a)), and the qualitative chemical composition showed Ca, P, Ka, C and O, indicating that the material attached in the crack corresponds with biological fluids that remain.

4. Conclusions

The supracondylar blade plate analyzed in this investigation failed due to the particular curvature and poor quality of the bone gave a weak primary fixation. The plate screws in the bone were fixed with an initial tension stress; this condition promotes fatigue by the natural movement of the patient during cyclic load/unload; these factors worked in a synergistic manner causing fracture after only four months of service. This analysis illustrates the importance of the design of orthopedic implants besides the fixation procedure and the compatibility with different morphology bones.

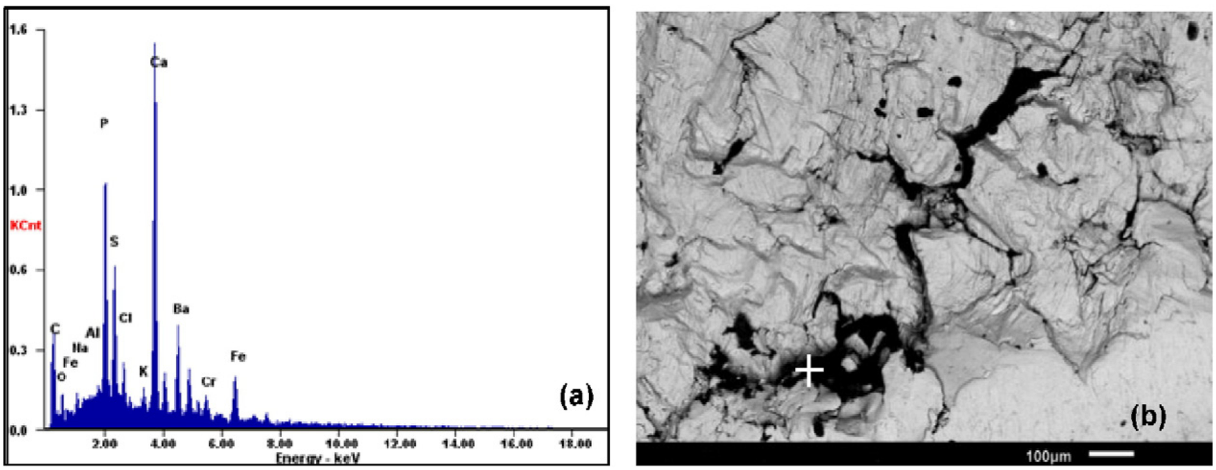

Fig. 6. (a) EDS analysis in the (b) crack artifacts, region of analysis identified (+).

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