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Notch sensitivity jeopardizes titanium locking plate fatigue strength

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ABSTRACT

Introduction: Notch sensitivity may compromise titanium-alloy plate fatigue strength. However, no studies providing head-to-head comparisons of stainless-steel or titanium-alloy locking plates exist.
Materials and methods: Custom-designed identically structured locking plates were made from stainless steel (F138 and F1314) or titanium alloy. Three screw-hole designs were compared: threaded screw-holes with angle edges (type I); threaded screw-holes with chamfered edges (type II); and non-threaded screw-holes with chamfered edges (type III). The plates' bending stiffness, bending strength, and fatigue life, were investigated. The stress concentration at the screw threads was assessed using finite element analyses (FEA).
Results: The titanium plates had higher bending strength than the F1314 and F138 plates (2.95:1.56:1) in static loading tests. For all metals, the type-III plate fatigue life was highest, followed by type-II and type-I. The type-III titanium plates had longer fatigue lives than their F138 counterparts, but the type-I and type-II titanium plates had significantly shorter fatigue lives. All F1314 plate types had longer fatigue lives than the type-III titanium plates. The FEA showed minimal stress difference (0.4%) between types II and III, but the stress for types II and III was lower (11.9% and 12.4%) than that for type I.
Conclusions: The screw threads did not cause stress concentration in the locking plates in FEA, but may have jeopardized the fatigue strength, especially in the notch-sensitive titanium plates. Improvement to the locking plate design is necessary.

Introduction

Locked plating is widely recommended for the treatment of various kinds of bodily fractures [1], having the advantages of high fixation stability [2] and the capacity for implementation with minimal tissue injury [3,4]. Commonly used materials in locking plate systems include stainless steel and titanium alloy. The latter has been particularly advocated recently because of its advantages compared with stainless steel: greater biocompatibility, fewer resultant artifacts on computer tomographic scans and magnetic resonance images, higher fatigue strength, and closer elasticity to that of bone [5,6]. However, the greatest titanium-alloy-related concern in comparison with stainless steel is its notch sensitivity [7], which may significantly jeopardize its fatigue strength leading to a higher risk of implant breakage and fixation failure. This notch sensitivity effect, which has been reported in locking plates [8], locked nails [9], and spinal transpedicle fixation devices [10,11], is particularly prominent at locations of abrupt geometrical changes, such as nail holes or screw threads, which are also locking plate features.

No head-to-head comparisons between the mechanical properties of locking plates made from stainless steel and from titanium alloy have been conducted. Therefore, the aims of this study with a head-to-head comparison were: (1) to compare the mechanical properties, including the bending stiffness, bending strength, and fatigue lives, of identically structured locking plates made of stainless steel or titanium alloy; (2) to investigate the screw-hole and thread-induced stress concentration and notch effects on locking plates.

Materials and methods

Test plate structures

The specially designed locking plates were made from either stainless steel (F138 and F1314) or titanium alloy (Ti6Al4V, F136-96) (Carpenter Technology, Reading, PA, USA) following ASTM specifications (American Standard of Tested Materials). The F138

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(AISI 316L), F1314, and titanium alloy tensile strengths were 560, 831, and 988 MPa, respectively. The plate structures and screw holes were modeled on commercially available implants (Periarticular distal femoral locking plate, Zimmer, Warsaw, IN, USA), with lengths, widths, and thicknesses of 130, 18, and 5.05 mm, respectively (Fig. 1). Three plate types with the same structures but different screw-hole geometries were manufactured: Type I had threaded holes with angle edges; type II had threaded holes with chamfered edges; and type III had non-threaded holes with chamfered edges (Fig. 2). The chamfer was made using a 45° oblique cut to remove the first thread of the screw hole. Each plate had three screw holes in the center with 16-mm separation between neighboring holes. The outer diameter of the screw holes was 8 mm.

Biomechanical tests

Four-point bending tests (ASTM F382-14) were conducted on the locking plates (Fig. 3). A bending load was applied on the concave surface of each plate to simulate "worst-case scenario" clinical conditions. Both plate ends were supported by two metal rollers with 110-mm spans, and the loading was applied at the center of the plate by two metal rollers with 60-mm spans. Plate movement during the cyclic loading was prevented by two bars inserted in the slots at the plate ends.

First, static loading tests were conducted on six samples of each plate type by applying a ramp-down load with a loading rate of 1 mm/min in displacement control mode using a materials testing machine (Bionix 858, MTS Corporation, Minneapolis, MN, USA). The loading continued until the plates were permanently deformed and the tests were terminated when the displacement of the actuator reached 6 mm. Then, with the same testing setup, dynamic fatigue loading tests were conducted using 10-Hz cyclic sinusoidal loading on six other samples of each plate type using a fatigue rated load cell. The maximum load (2300-N) was 120% of the bending strength of the F138 plates obtained in the static-loading tests (the choice of this value is explained below), and the stress ratio of the minimum to maximum load in one loading cycle was 10%. The tests were terminated when the displacement of the actuator was beyond 5 mm with a visible crack or when the fatigue life was over 10^6 cycles. For plates that did not fail the cyclic loading tests with this maximum load for 10^6cycles, the maximum load was increased to 3500-N (120% of the bending strength of the F1314 plates), and the tests were repeated using 6 new plates for each type.

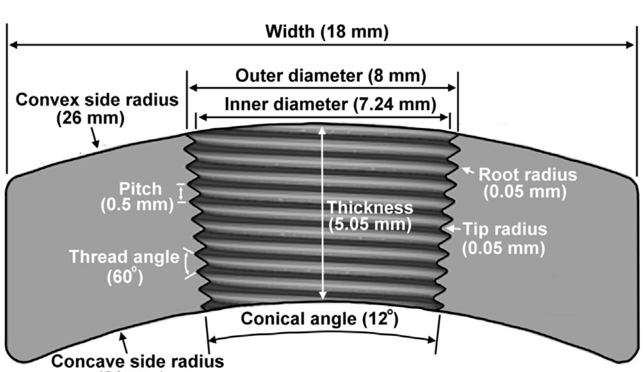

Fig. 1. Basic plate and threaded screw-hole geometries and dimensions.

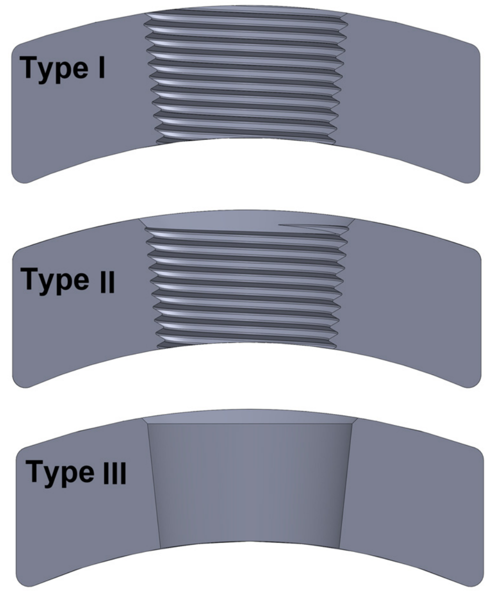

Fig. 2. Three locking plate types with different screw thread designs: Type I with threaded holes and angle edge; Type II with threaded holes and chamfered edge; Type III with non-threaded holes and chamfered edge.

Failure analysis

Failure analyses including material analysis, fractographic examination, and metallographic examination were performed on all broken plates. The fracture surfaces were examined using a scanning electron microscope (SEM, 250–5,000×, Hitachi S-4800, Hitachi High Technologies, Tokyo, Japan). The sectioned surfaces of the plates were prepared and observed under an optical microscope. The micro-cleanliness and grain size were determined according to ASTM E45 and E112 standards, respectively.

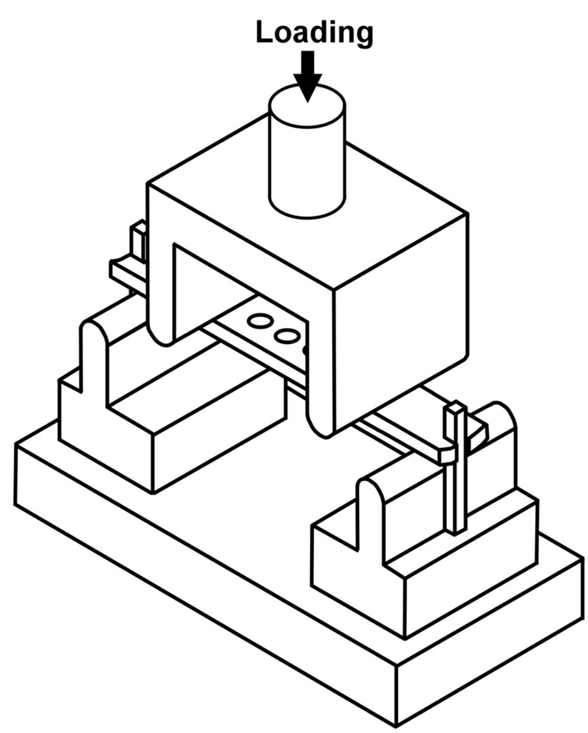

Fig. 3. Four-point bending tests conducted on the locking plates with bending load applied on the concave surface of each plate.