Clinical Biomechanics 54 (2018) 71–77

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Modification of the screw hole structures to improve the fatigue strength of locking plates

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ARTICLE INFO

Keywords:
Titanium locking plate
Fatigue strength
Screw hole structure

ABSTRACT

Background: The fatigue fracture of locking plates can substantially threaten fracture treatment results. In the present study, three measures for modifying the screw hole structures of plates were implemented to improve their fatigue strength.
Materials: Custom-made identical titanium locking plates, except the screw hole configurations, were tested using four-point bending load. The three measures were partial removal of screw threads on the tension side of the plates, reduction of screw hole size, and modification of the thread radii. There were six types of plates: control (Type I), half of the threads removed (Type II) or one-third of the threads (Type III), smaller screw holes (Type IV), and increase of the thread root radii (Type V) or crest radii (Type VI).
Findings: Compared with the control, Types II and III significantly improved the fatigue strength (14.5 and 10.1 times, respectively). Decreasing the size of the screw hole (Type IV) also yielded a higher fatigue strength (17.6%). Type VI significantly improved the fatigue strength (9.8 times). However, Type V decreased the fatigue strength (14%). For cyclic stiffness, Type IV was significantly higher than other types statistically. Failure analyses showed typical fatigue fracture in all plates and the cracks were always initiated at the thread crest.
Interpretations: The fatigue strength of titanium locking plates can be significantly improved by structural changes in the screw holes. Removing the threads of the plates and increasing the crest radii of the threads were more effective measures than decreasing the size of the screw holes.

1. Introduction

Locking plates with locking head screws fastened in the threads of screw holes can preserve vascular supply to the injured bone and achieve stronger fracture fixation compared with conventional dynamic compression plates (Arnone et al., 2013; Kanchanomai et al., 2010; Smith et al., 2007; Sommer et al., 2004). Owing to the additional advantage of minimal injury technique, locking plates have been widely recommended for the treatment of various types of fractures (Smith et al., 2007; Strauss et al., 2008). Locking plates are particularly preferred to intramedullary nails for metaphyseal fractures with short and wide end fragments because they can provide more reliable fixation in the short metaphyseal bone fragment, and their anatomical configuration, which need not be contoured to fit the bone, can facilitate the operation (Gautier & Sommer, 2003; Hoffmann et al., 2013; Smith et al., 2007; Strauss et al., 2008). However, premature mechanical failure of the hardware is still a significant threat to the use of locking plates (Hoffmann et al., 2013; Kanchanomai et al., 2008; Smith et al., 2007; Sommer et al., 2004; Strauss et al., 2008). It may lead to fixation failure and disastrous complications, which often require surgical re-interventions and may lead to protracted recovery and increased patient discomfort. Material fatigue after multicyclic loading is the most commonly observed failure mode (Hoffmeier et al., 2011). Nowadays, the most commonly used materials for manufacturing locking plates include stainless steel and titanium. The use of the latter has been particularly advocated recently owing to certain advantages: higher biocompatibility, fewer resultant artifacts on computer tomographic scans and magnetic resonance images, higher fatigue strength, lower infection risk, and isoelasticity to bones (Hayes & Richards, 2010). However, although it has high fatigue strength, titanium may lose its fatigue strength drastically in certain circumstances because of the property of severe notch sensitivity, a measure of material strength reduction caused by the presence of a notch or other stress raisers (Dick & Bourgeault, 2001). This notch sensitivity effect has been reported in locking screws, locked nails (Hsu et al., 2010), spinal transpedicular fixation devices (Chen et al., 2003), and locking plates (Tseng et al., 2016). In locking plates, the fatigue strength of titanium plates may be markedly decreased by the threads in the screw holes (Tseng et al.,

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https://doi.org/10.1016/j.clinbiomech.2018.03.011
Received 31 December 2017; Accepted 16 March 2018

2016). Besides, it has also been observed that the thread crest has the highest stress under bending load and tends to be the fatigue crack initiation site. This indicates that the fatigue strength of the plates might be related to the structures of the internal threads of the plate holes and can be improved.

Therefore, in the present study, three measures for new screw hole designs were developed to reduce notch sensitivity effects and improve the fatigue strength of plates. These measures include partial removal of threads, decreasing the size of the screw holes, and modification of the thread radii. In total, six types of plates, five new designs, and one control were specially manufactured and mechanically tested. Further, their fatigue strengths and failure modes were analyzed and compared.

2. Methods

2.1. Structures of the tested plates

The plates for the fixation of femoral fractures were simulated in this study because they sustain high physiological loads and are prone to mechanical failure (Arnone et al., 2013). The specially designed locking plates were made from titanium alloy (Ti6Al4V, F136-96) (Carpenter Technology, Reading, PA, U.S.A) with a yield strength of 862 MPa, tensile strength of 910 MPa, and elongation rate of 16%. The plate and screw hole structures were modeled on commercially available implants (Periarticular distal femoral locking plate, Zimmer, Warsaw, IN, USA), with lengths, widths, and thicknesses of 140, 18, and 5.05 mm, respectively. The curvature was 26° for the convex side and 21° for the concave side. To ensure a fair comparison, the plates were manufactured with identical structures, except the configurations of the holes and threads (Fig. 1). The plates had three round holes in the middle with a distance of 14 mm between each adjacent hole. In total, there were six types of locking plates (Fig. 2) (Table 1). Type I with ordinary fully threaded holes was the control group. Type II plate was the same as Type I, except that half of the screw threads at the tension side of the plates were removed. Type III was the same as Type I except that one third of the screw threads at the tension side of the plates were removed. Type IV was the same as Type I except that the screw hole diameter was reduced to 7 mm. Compared with Type I, Type V had larger root radii (0.05 vs. 0.20 mm) and Type VI had larger crest radii (0.05 vs. 0.20 mm). All the screw holes had a 45° chamfer on the hole edge at the tension side of the plates.

2.2. Mechanical tests

2.2.1. Cyclic loading tests

Four-point bending tests were conducted on the locking plates according to the ASTM F382-14 standard because it could simulate “worst-case scenario” clinical conditions (Fig. 3) using a servo-hydraulic material testing machine (model 8872; Instron Industrial Products, Grove City, PA, USA). Both plate ends were supported using two metal rollers with 120-mm spans, and loading was applied at the center of the plate using two metal rollers with 60-mm spans. Plate movement during cyclic loading was prevented using two bars inserted in the slots at the plate ends. Dynamic fatigue loading tests with a sinusoidal waveform were conducted on 10 new plates of each type with a loading rate of 10 Hz. The plates were loaded at the middle according to the loading in a previous study (Tseng et al., 2016), with a maximum load of 2100 N (120% of the bending strength of the F138 plates obtained in the single-loading tests) with a stress ratio (minimum load/maximum load in one cycle) of 10%. The tests were terminated when the displacement of the actuator was beyond 6 mm with visible cracks. The number of loading cycles at plate failure was recorded. The cyclic stiffness was also calculated when the loading deformation was stable. Finally, the failure of the plates was investigated.

2.2.2. Statistical methods

Analysis of variance (SPSS v22.0, SPSS Inc., Chicago, IL, USA) was used to compare the differences in the fatigue life and cyclic stiffness among the six types of plates. The LSD test was used for post hoc comparison. The level of significant difference was defined as $p < 0.05$.

2.3. Failure analysis (fracture surface examination)

All the fractured plates were carefully protected to prevent damages to the fracture surfaces. Then, the fracture surfaces were thoroughly cleaned and irrigated for further examinations.

2.3.1. Optical microscopic examination

The fracture surfaces were examined using an optical microscope. The fracture configuration, crack initiation site, and propagation direction were observed.

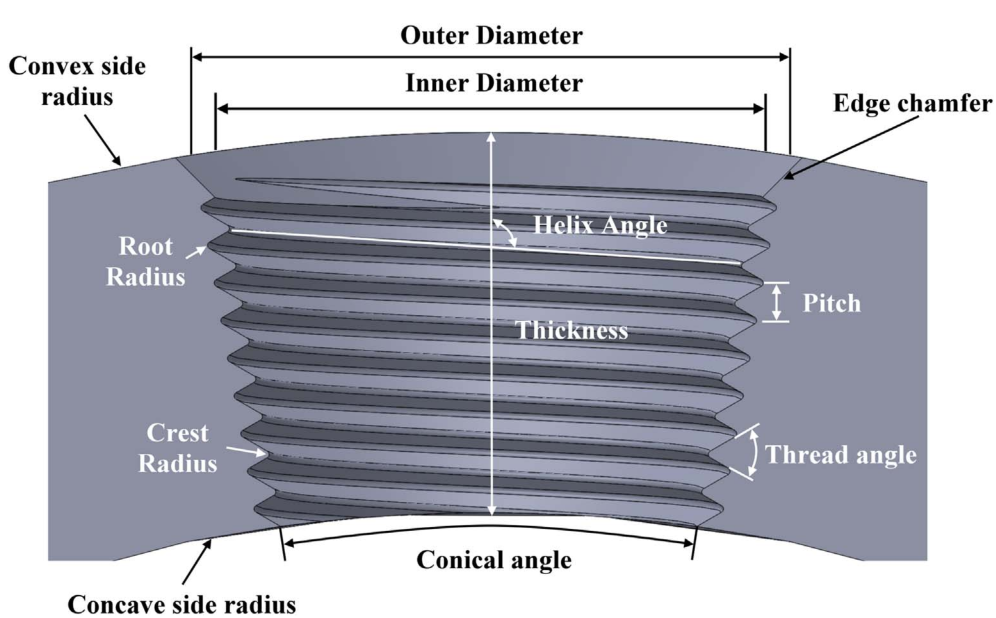

Fig. 1. Nomenclatures of the screw hole structures.