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Enhancing the durability of spinal implant fixture applications made of Ti-6Al-4V ELI by means of cavitation peening

Osamu Takakuwa [a,*], Masaaki Nakai [b], Kengo Narita [b], Mitsuo Niinomi [b], Kazuhiro Hasegawa [c], Hitoshi Soyama [a]

[a] Department of Nanomechanics, Tohoku University, 6-6-01, Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
[b] Institute for Materials Research, Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai 980-8577, Japan
[c] Niigata Spine Surgery Center, 2-5-22, Nishimachi, Konan-ku, Niigata 950-0165, Japan

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ABSTRACT

The surface treatment technology known as ‘cavitation peening’ was employed in this study in order to enhance the durability of spinal implant fixture applications, which are subject to fretting fatigue. Cavitation peening can be realized by a technique in which a high-speed water jet is injected into water through a nozzle. It utilizes a phenomenon by which surface impacts due to collapsing cavitation bubbles induce work-hardening by introducing residual compressive stress near the surface. A fretting fatigue test was conducted on a spinal implant rod made of Ti-6Al-4V ELI in accordance with the ASTM F1717 standard, which is the established method for testing spinal implants after they are treated by cavitation peening. The residual stress was evaluated by using X-ray diffraction analysis. The hardness over the cross-sectional area was also measured using an indentation test. The obtained results show that cavitation peening drastically improves the fretting fatigue properties of spinal implant fixtures by as much as 2.2 times compared to untreated ones. This can be attributed to a significant increase in the hardness from 5.0 to 9.6 GPa and a high compressive residual stress of over 600 MPa induced by cavitation peening.

1. Introduction

The present study demonstrates significant enhancement of the durability, i.e., fretting fatigue strength, of the titanium alloy Ti-6Al-4V ELI (Extra-Low Interstitial), as used for spinal implants, by the application of cavitation peening, which is a recognized surface modification technique. Recently, the rapid increase in the number of elderly persons in the population has led to an increasing demand for innovative biomedical materials to be used for artificial implants [1–3], e.g., bone plates, hip joints and spinal fixation. Titanium alloy is widely used in applications from turbine blades to biomedical materials because of its favorable properties, i.e., high strength, light weight, high corrosion resistance and high biocompatibility. In order to use titanium alloys for the fixation of spinal implants in the form of rods, screws and plugs, its reliability needs to be further enhanced, particularly in terms of its resistance to fretting fatigue, wear, and corrosion [4–9], since it is hard to replace an implant rod once it has broken. For spinal implant fixation, the fretting fatigue and fretting wear that occur between the rod and the holding fixture is a well-known problem. This fracture phenomenon should be prevented in order to realize highly-reliable biomaterials for spinal implants. Several titanium alloys have been developed to achieve the good mechanical properties mentioned above, as well as good biocompatibility [10–12]. Coating of the surface results in high resistance to wear in ‘metal-on-metal’ situations and may be effective in the field of joint replacement. In cases in which the surface is subjected to both fatigue and wear, i.e., fretting fatigue, improvement of the surface mechanical properties of the metal would be more effective.

One way to enhance the mechanical properties and the tribology characteristics is by the introduction of a hardened layer and compressive residual stress into the surface. Peening techniques can introduce these characteristics due to plastic deformation (i.e., work hardening) induced by a large number of impacts on the surface. There are some notable peening techniques, such as shot peening, which utilizes impacts between solid bodies, laser peening, which utilizes impacts generated by laser abrasion, and cavitation peening, which utilizes impacts due to the collapse of cavitation bubbles. Peening enhances resistance to fatigue

* Corresponding author.
E-mail address: o_takakuwa@mm.mech.tohoku.ac.jp (O. Takakuwa).

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[13–17], stress corrosion cracking [18,19] and hydrogen embrittlement [20,21]. In general, peening has been applied for the treatment of mechanical components, e.g., automotive components, and large structural components, e.g., the shrouds installed in a nuclear power plant, etc. Many studies have been performed to investigate the effect of peening on the fretting fatigue properties of several alloys [22–25]. However, it is comparatively hard to apply peening on small targets that have a curved structure, such as spinal implant rods (~5 mm in diameter). In addition, beneficial effect of peening on a spinal implant rod subject to the fretting fatigue has not been clarified yet based on a method specialized in the verification of the spinal implant. In order to apply cavitation peening to improve the durability of the spinal implant fixation, the beneficial effect of cavitation peening has to be obviously demonstrated. For this reason, there has been an attempt to enhance the reliability of the titanium alloy used for spinal implant rods by use of a peening technique. Although it has been reported that cavitation peening and laser peening can introduce high compressive residual stress into Ti-6Al-4V ELI implants [26,27], there have been no demonstrations of the enhancement of fretting fatigue properties when simulating the usage of spinal implants. Thus, in this paper, a specialized fretting fatigue test for spinal implant rods was conducted in accordance with ASTM F1717 [28], which is a standardized method for endurance-testing of spinal fixation models after treatment by cavitation peening.

Cavitation frequently causes severe damage to hydraulic machinery, e.g., pumps and propellers, since the surfaces are subjected to a large number of impacts that are generated when cavitation bubbles collapse. Cavitation bubbles are generated as pressure decreases below the vapor pressure due to increasing velocity, and they subsequently collapse as the pressure and velocity are restored. Therefore, the collapsing causes a large impact, in the order of GPa, which induces severe plastic deformation at the surface of metallic materials. The addition of a jet that includes cavitation bubbles, i.e., a 'cavitating jet', has been successfully applied as a method of peening metallic materials. The resulting so-called 'cavitation peening' utilizes the impact energy arising from the collapse of the cavitation bubbles. So far it has been demonstrated that the life-times of gears [29] and of continuously-variable transmission (CVT) elements [30] can be greatly improved by this technique, in addition to the suppression of hydrogen embrittlement [21]. It has also been demonstrated that cavitation peening enhances resistance to fretting fatigue on a Ti-6Al-4V plane surface [31,32]. In order to apply the cavitating jet technique to a small rod, the ambient pressure needs to be controlled to generate a suitable jet shape. When applied to a plate-like surface, cavitation bubbles are still growing after the jet impinges on the surface and they then collapse. However, in the case of small rod shape, the cavitation bubble needs to be sufficiently developed in the jet, since it cannot grow well on the rod surface. The 'collapse area' of the cavitation bubbles can be controlled by the ambient pressure. At low ambient pressure, e.g., atmospheric pressure, cavitation bubbles collapse over a large area and the number of cavitation bubbles collapsing per unit area is relatively low. Conversely, at high ambient pressure, the cavitation bubbles collapse within a small area, and the number of cavitation bubbles collapsing per unit area is relatively high. In order to effectively treat the surface of a metallic rod that is only several millimeters in diameter, the ambient pressure needs to be raised much higher than atmospheric pressure in order to induce the cavitation bubbles to collapse intensively within a small area.

In this study, cavitation peening has been employed in order to enhance the fretting fatigue properties of a spinal implant rod of 5 mm in diameter manufactured from titanium alloy Ti-6Al-4V ELI. The injection pressure was set at 80 MPa and the ambient pressure was kept much higher than atmospheric pressure at 0.8 MPa in order to treat the small rod effectively. The treatment was carried out over several different processing times. After the treatment, residual stress, and surface roughness and hardness were evaluated by X-ray diffraction employing 2D-XRD using a two-dimensional detector, by a stylus method and by a nano-indentation test, respectively. Endurance testing was then conducted in accordance with the ASTM F1717 standard.

2. Experimental apparatus and procedures

The material under test was manufactured from medical-grade titanium alloy rod Ti-6Al-4V Extra Low Interstitial (ELI), produced by Perryman Company. The chemical composition is shown in Table 1. The rods had a diameter of 5 mm and a length of 100 mm. The rods were annealed for 1 h at 700 °C. The yield strength, defined as 0.2% offset stress, and the tensile strength were 943 MPa and 1049 MPa, respectively. The rods were manufactured in accordance with ASTM F136 standard established for material testing of spinal implant fixtures.

2.1. Cavitation peening of spinal implant rods

A schematic diagram of the cavitating jet apparatus and the nozzle shape used for the experiments are shown in Figs. 1 and 2, respectively. The high-speed water jet was pressurized by a plunger pump that has a maximum pressure of 300 MPa, and was injected into the test section through the nozzle. The injection pressure, p_1, was controlled by the velocity of the inverter motor connected to the plunger pump. The test section's ambient pressure, p_2, was controlled by the downstream valve.

The cavitating jet significantly changes its shape and aggressive strength as a function of the cavitation number, σ. Generally, the cavitation number is defined by the ratio of the hydrodynamic pressure and the static pressure at the cavitating flow [33]. In the case of the nozzle and the orifice flows, the cavitation number of a cavitating jet can be defined by Eq. (1), as a function of the injection pressure p_1, the ambient pressure p_2, and the vapor pressure of the test water, p_v.

$$\sigma = \frac{p_2 - p_v}{p_1 - p_2} \cong \frac{p_2}{p_1} \quad (1)$$

Simplification of the above relationship is possible since $p_1 \gg p_2 \gg p_v$. The aggressive intensity of the cavitating jet has a maximum at around $\sigma = 0.014$ [34].

Table 1
Chemical composition of the Ti-6Al-4V ELI.

Element	O	N	C	Fe	Al	V	Si	Cu
Content (wt.%)	0.12	0.007	0.017	0.18	6.16	4.05	0.019	0.005

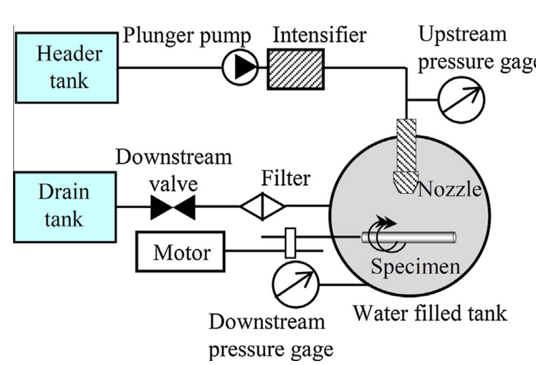

Fig. 1. Apparatus for cavitation peening employing a cavitating jet in water.