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Fabrication and tribological behaviors of corner-cube-like dimple arrays produced by laser surface texturing on medical needles

Xingsheng Wang [a,b,*], Marco Giovannini [b], Youqiang Xing [b,c], Min Kang [a], Kornel Ehmann [b]

[a] College of Engineering, Nanjing Agricultural University, 40 Dianjiangtai Road, Nanjing, Jiangsu 210031, PR China
[b] Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA
[c] Department of Mechanical Engineering, Shandong University, Jinan 250061, PR China

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ABSTRACT

Micro-corner-cube-like dimples with various geometrical characteristics were fabricated on the surface of medical needles by laser surface texturing. The effects of geometric parameters of dimples on tribological behaviors were investigated by carrying out insertion tests. It was found that the textured surface with a dimple array increased the friction between the needle and phantom tissue because of stress concentrations near the edges. Furthermore, the drag increment rate increased with the increase of dimple size and circumferential number, while dimple depth had no significant effect on the friction. The minimal drag increment rate was achieved at a medium value of spacing. The geometric parameters of dimples could be varied to control area density that indirectly affect the friction behavior.

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1. Introduction

Medical needles are widely used in various minimally invasive percutaneous procedures such as tissue biopsy, regional anesthesia, blood sampling, brachytherapy, catheter insertion, abscess drainage and deep brain biopsy [1,2]. The success of these procedures depends on the accurate placement of the medical needles for either drug delivery or tissue sample removal. The placement errors of the medical needles cause vital tissue damage, under/over dosing with radiation, misdiagnosis, etc. [3]. It has been shown by clinical studies that tissue inhomogeneity and anisotropy, tissue deformation and movement, unfavorable anatomic structures, needle bending and imaging limitations mainly contribute to the inaccurate needle placement [2,4]. Some of the factors like tissue deformation and movement and needle bending have a high dependence on the forces experienced by the needle during the percutaneous procedure. Thus, a practical approach to improve needle placement accuracy is to minimize the insertion force [1].

Another possible method to reduce needle placement errors is to improve needle visibility during needle insertion. There are various strategies to increase needle visibility, including systematic manipulation of the needle and transducer to ensure needle-beam alignment, development of echogenic needles, and advances in ultrasound imaging technology [5]. Among these strategies, echogenic needle design is an economic and reliable method of improving needle ultrasound visibility. Micro-dimples, micro-corner reflectors, and micro-channels are often created near the needle tip to serve as ultrasound wave reflectors [5–8]. It has been verified both in laboratory and clinical setting that echogenic needles with micro-features provide superior visibility under sound guided percutaneous procedures.

In recent years, various micro-features have been applied on mechanical seals [9,10], automotive components [11–13], cutting tools [14–16] and other mechanical components [17,18] to improve friction behavior and wear performance as well as to extend the life of mechanical components. Under dry sliding conditions, it was demonstrated that the micro-features were able to trap loose wear debris from the contact surface [13,17]. While, the micro-features could also influence lubrication mechanisms under wet conditions, leading to beneficial changes in friction and wear properties [18,19]. Previous research focuses on the friction behavior between two hard surfaces. A few literatures dealt with the tribological characteristics between a textured hard surface and soft materials such as soft tissue and elastomer. Han et al. [20] fabricated an array of micro-channels with various channel widths, area densities and channel orientations on needles to study the effect of textured needles on the friction. It was found that such texture patterns increased the friction during needle insertion due to the stress concentrations at the edges of the channels. Valasquez et al. [21] investigated the friction between surgical blades with micro-dimples and soft tissue. Blades with the blended dimple rims showed a reduction in cutting friction. In spite of the fact that corner-cube dimples were widely used as

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* Corresponding author at: College of Engineering, Nanjing Agricultural University, 40 Dianjiangtai Road, Nanjing, Jiangsu 210031, PR China.
E-mail address: xingshengwang@njau.edu.cn (X. Wang).

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reflectors for signals returning due to the high reflectivity, no studies to date have been carried out to study the tribological behaviors of needles with micro-corner-cube dimples during needle percutaneous procedure.

In this paper, laser surface texturing (LST) is used to fabricate micro-corner-cube-like dimples on the medical needles. Additionally, friction tests between the laser surface textured needles and phantom tissue are performed to study the effect of geometric parameters of dimples on the friction behavior. The objective is to understand the friction behavior between a textured hard medical needle and soft tissue and to determine the optimal geometric parameter of corner-cube-like dimples that would minimize the friction during needle insertion procedure. The results from this work will serve as the basis for developing echogenic needles with lower insertion forces.

2. Experimental details

2.1. *Fabrication of corner-cube-like dimples*

AISI 304 stainless steel solid needles (Mick Radio-Nuclear Instruments Inc.) with a diameter of 1.8 mm and a bevel angle of 15° were used in this study. Laser surface texturing was carried out on the surface of the medical needles by a commercial diode-pumped Nd:YVO_4 laser (Lumera Lasers Inc.) with a wavelength of 532 nm and a pulse duration of 8 ps. The laser beam with Gaussian distributed profile was focused to a spot with a diameter of 10 μm using a 25 mm focusing lens. The operating frequency was set to 100 kHz at an average power of 0.6 W, yielding a pulse energy of 3 μJ, as measured by an external power meter (Gentec Solo2). The needle, kept in air at room temperature, was mounted on a 5-axis motion stage (Aerotech Inc.) with a translation resolution of 10 nm and rotational resolution of 0.0001°.

A triangular trajectory similar to that of a milling cutter performing a pocketing operation and a layer-by-layer scanning strategy was employed to create corner-cube-like dimples (for more details, see Ref. [22]). Fig. 1 shows a schematic diagram of corner-cube-like dimple array on the needle. The dimple size was set at 100, 200 and 300 μm in width and spacing ranging from 0.2 to 0.6 mm. Each needle segment was graduated all-round with dimples at specified offset angle that was determined by circumferential number. Pulse overlap in the feed direction was varied to control the machined depth of the dimples. The length of textured surface was 9.6 mm. The geometric parameters of corner-cube-like dimples used in this study are listed in Table 1. The area density was calculated by using the formula $D_{area}=S_{dim}/S_{area}\times 100\%$, where S_{dim} is the area of all the dimples created on needles and S_{area} is the area of the textured surface.

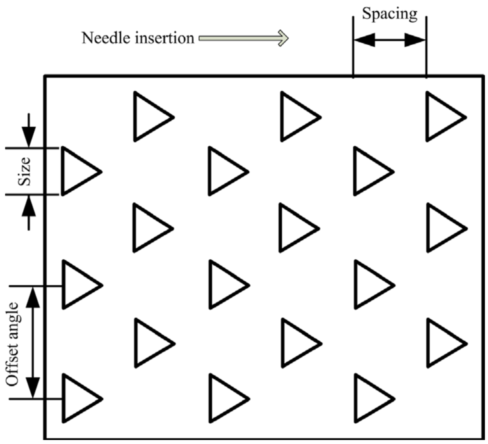

Fig. 1. Schematic diagram of corner-cube-like dimple array on the medical needle.

2.2. *Friction test*

Friction tests were carried out using a specially designed setup for needle insertion, as shown in Fig. 2. It consists of a linear motor module, a needle fixture, a tissue fixture and a piezoelectric force dynamometer. The Copley linear motor module was used to perform one-dimensional translational motion. This motor delivers a continuous force of 51 N with a peak force of 312 N. The resolution of the linear encoder that measures the needle's axial/insertion position is 12 μm. The maximal velocity is 8.5 m/s with a peak acceleration of 222 m/s^2. The linear motor module is controlled by a Copley Xenus digital drive (model: XTL-230-18-S) communicating via RS-232 by using the CME 2 software. The three-component piezoelectric dynamometer (Kistler 9067) was mounted beneath the tissue fixture to measure the needle insertion force. The sensitivity of the force sensor is -8 pC/N for the X- and Y-axis and -3.8 pC/N for the Z-axis. The threshold is less than 0.01 N. All the data were recorded with a NI Data acquisition board DAQ Card – 6036E and processed using LabView-based software. The maximal sampling rate of the DAQ is 250 kHz per channel.

To measure the insertion force, the needle was inserted approximately 14 mm into the phantom tissue. Friction was measured while the needle was inserted into the tissue, as illustrated in Fig. 3. The phantom tissue used for the tests was composed of 8116SS plastic with 4116 S plastic softener (M-F Manufacturing, Texa) in a 4:1 ratio. The mixture was heated to 180° and then poured into a mold to create 50 mm (long) × 50 mm (wide) × 4 mm (thick-direction of needle insertion) phantom blocks. This phantom tissue was commonly used as tissue-mimicking material during needle insertion tests due to its homogeneity [3,23]. The tissue was attached to the stage platform using double-sided tape to keep a constant pressure. The insertion velocity was kept constant at 20 mm/s. Each test was repeated

Table 1
The geometric parameters of dimple arrays on needles.

Needle no.	Size (μm)	Spacing (μm)	Circumferential number	Depth (μm)	Area density (%)
S0	0	0	0	0	0
S1	100	0.4	8	30	1.5
S2	200	0.4	8	40	6.1
S3	300	0.4	8	50	13.8
S4	100	0.2	8	30	3.1
S5	100	0.6	8	30	1.0
S6	100	0.2	8	20	3.1
S7	100	0.2	8	10	3.1
S8	100	0.2	6	30	2.3
S9	100	0.2	10	30	3.8

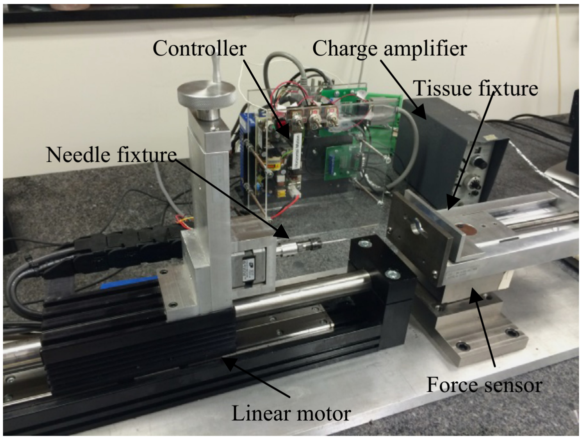

Fig. 2. Experimental setup for needle friction test.

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