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A novel strain energy density algorithm for laser-induced micro-hollows

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ABSTRACT

Mechanical adaptation and stability of implants are dependent on strain energy density algorithms of their surfaces. These applications are in their early stage, but theoretical predictions show us that we can manufacture very strong, flexible biomaterial surface which has a shock absorbing ability. Laser micro-machining is a clean tool for biomedical industry. The purpose of this manuscript is to consolidate a laser micro-machining method for imitating lotus effect on commercially pure titanium specimen surfaces and to develop a novel strain energy density algorithm. Novel 3D nelumbo leafs were prepared using a fiber laser ($\lambda = 1060$ nm) with 200–250 ns pulse durations and optimum operation parameters were suggested.

1. A double-edged sword which was found in a deep abandoned well: "strain"

The characteristics of a biomaterial surface govern its biological and mechanical response [1,2]. For this reason, methodical development of biomedical surface technologies has a crucial importance. Well defined surface morphology was the most critical concept in bone remodeling studies from the viewpoint of sufficient micro-mechanical interlocking [3]. Many investigations were conducted to increase the bone volume at the implant surface. Thus it can be deemed as necessary indispensable factor in the development of biomedical surface technology. Appropriate surface micro topography is still an unknown secret. However, osteocyte is a key component and it sends mechanical signals in all directions with activating osteoblasts and osteoclasts [4] and hydrophilic surfaces are promising. The invention of the first *"scanning electron microscope"* was made by Lane, in the 1970 [5]. In 1977, Barthlott and Ehler focussed on an electron microscope [6]. They succeeded in examining the leafs of the Nelumbo. Thus, lotus effect concept was first mentioned by Barthlott in 1990 [7,8]. It refers to the very high water repellence exhibited by the leaves of the lotus flower. One year later, Carter et al. claimed the first idea of a control system [9]. In 1995, Mullender and Huiskes redeveloped the mechanical adaptation theory via strain energy with their computer-based model [10]. Mechanoregulation mechanisms were investigated by strain experts with using finite element studies [11,12,13,14,15]. Prendergast and Huiskes suggested that the remodeling stimuli could be generated in response both micro damage and strain to maintain bone mass simultaneously [16]. In 2001, Burger and Klein-Nulend reported sensoring activities of cells as; *"there is a bone cell network that links the bone cell signal due to strain to a cellular signal, which causes bone resorption or bone formation"* [17,18]. Thus the chains of biochemical response might be triggered with little perturbations in strain. Such evidence does not constitute adequate support for the theory and it requires some explanations for controlling such a critical aspect. Then McNamara and Prendergast reported a mechanoregulatory system based on combination of strain and damage stimuli. They emphasized that there were two approaches for mechano-sensoring applications of cells; surface sensors and osteocyte sensors. Osteoblast and lining cells can be stimulated by nano-scale based modifications for surface based remodeling. It is obvious that they have not remarkably effect on mechanical interlocking [19,20,21]. However, micron-scale based modifications are required for internal cell (osteocyte) based bone remodeling operations. Recently, Schulte et al. redefined a mechanical stimulus function; it was similar to the Frost and Turner's mechanostat theory [3,22–24]. Some authorities implied that these scientific movements were determined from the general demeanor in achieving actual strains [25]. There are some facets for selecting appropriate surface manufacturing methods such as biomedical function, purpose, method limitations and options. The laser treatment due to its benefits i.e. cleanliness seems to be a promising manufacturing process for preparation of artificial lotus leafs. Considerable amount of research has been devoted to find some manufacturing methods for the treatment of implants using lasers [26–29]. "*Frozen Melted Droplets*" phenomenon was first reported in a research manuscript by Peto et.al. [30]. They showed that submicron to ten microns morphological surface structures can be created with Nd: glass laser treatment.

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However, if we are argue that in these reports droplets were diffracted inhomogeneous way and they were not showing any systematic behavior it remains a matter of serious concern that there is no research on how we can shape this unstable tiny droplets in a periodical arrays and which process dynamics should be taken into account adjusting the right laser process parameters. Although considerable amount of research has been devoted to laser surface micro-machining for making micro to nano-scale surface irregularities until now, limited ability has existed for the micro-scale isotropic laser treatment with including regular sub-micro elements. Also on the other hand disproportionate attention has been paid to observe strain control mechanisms to minimize stress shielding effect between implant and bone. Therefore, it would seem reasonable to state that further methods are needed to manufacture new patterns for implant surfaces.

This paper will suggest two key issues which need to be addressed when considering the development of novel smart surfaces; a new hypothesis and a novel method. In the present paper, novel 3D nelumbo leafs were prepared using a fiber laser ($\lambda = 1060$ nm) with 200–250 ns pulse durations and optimum operation parameters were suggested and a strain energy density algorithm was presented as a control mechanism of interfacial strain energy. These surface patterns can play a significant role with controlling the interaction mechanisms of mechano-sensing signals between the bone and the implant surface. Metallic lotus leafs can be acted as flexible bearings to stimulate the activation energy at the first step and maintain inertia in movement for breaking the stress shielding effect at the bone-implant interfaces at the second step. Also these novel artificial osteoclastic resorption cavities can be called as *"micro-powertrains (MiPots)"*. They are supposed to pretend as micro-damaged tissue zones in the original bone with managing strain energy.

2. Materıal and method

2.1. 3D works for MiPots

In order to establish a strong mechanical adaptation, we developed 3D micron-scale regular cavities which have 41 μm and upper diameter values. (Fig. 1) 10 μm and upper surface roughness values were proposed for sufficient mechanical interlocking at the interface [30]. To form novel surface patterns as strain modulators, it was assumed that the cavities had been filled with bone to establish interfacial stability. These patterns can be considered as strain energy trains which mediate elasticity between the bone and implant and they form a reliable micro-mechanical interlocking. While frozen melted droplets can play a role as surface sensors with establishing high strain regions for osteoblast activity, micro-pores can work as osteocyte sensors. Thus they can establish mechanical interlocking together. With this way, these micro-cavities are supposed to be filled with surrounding fluid that supply the bone cells with nutrients and they provide a network for the bone cells for mechanical changes through artificial canalicular channels.

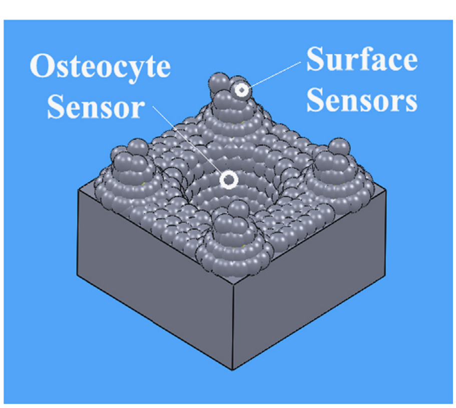

Fig. 1. Schematical representation of osteocyte and surface sensors.

Dimensional characteristics and densities of every individual structure have crucial influence on interfacial strain energy. Furthermore, understanding the whole functional characteristics of the implant surface allow us to evaluate the responses of bone. For this reason, a series of three-dimensional FEM models were performed to calculate interfacial tissue strain energies to evaluate the strain degrees of different designed micro-patterns. An anisotropic elastic model was adopted for the cortical bone. These data referred to experimental investigations using ultrasonic wave measurements that are reported by Dechow et al. [20]. Mechanical properties of materials used in this study are shown in Table 1. The optimal osseointegration concept was assumed and the applied load was carefully adjusted to the stress levels that bone can withstand [30]. The mesh number has been adjusted at the bone-implant interface as for the necessity of the precision outcomes.

According to the force boosting graph in Fig. 2, smaller micro-pits had better power generation performance than other patterns. They can suspense immediate loads with preventing stress shielding effect at the bone-implant interface thus they can be act as flexible bearings for active control mechanisms. The data indicated that the proposed model could greatly reduce "stress shielding effect" via controlling interfacial strain energy. Maximum interfacial strain energy was found for 55 μm pit pattern, it was decreased respectively from the 60 μm pit size. The estimated strain energy density value of 41 μm pit diameter was 9.28×10^{-10} mJ. And the SED values were 5.41×10^{-10} mJ and 1.71×10^{-10} mJ for the 61 μm pit and 91 μm pit patterns respectively. Smaller micro-pits had better strain energy performance than other patterns so they can suspense immediate loads with preventing stress shielding effect at the bone-implant interface thus they can act as active stimulators playing an important role in a strain control mechanism. The behavior of interfacial strain energy density can be stated with following

Table 1
Mechanical properties of materials used in FEM analysis.

Material		**Bone**	**Titanium**
Young modulus (GPa)	Exy	11.3	105
	Exz	13.8	–
	Eyz	19.4	–
Poisson's ratio	νxy	0.237	0.30
	νxy	0.376	–
	νxz	0.274	
Shear modulus (GPa)	Gxy	4.5	–
	Gxz	5.2	–
	Gyz	6.2	–

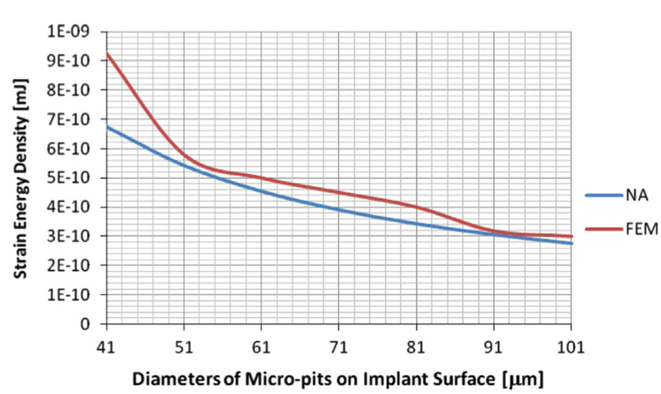

Fig. 2. Graphical representation of interfacial strain energy density analysis of micro-pit patterns.