European Journal of Mechanics / A Solids 71 (2018) 235–244

Contents lists available at ScienceDirect

European Journal of Mechanics / A Solids

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

The effects of waterjet peening on a random-topography metallic implant surface

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ARTICLE INFO

Keywords:
Waterjet peening
Rough surface
Impact velocity
Area roughness parameters

ABSTRACT

Surface roughening is often applied to various devices, such as orthopedic and dental implants, in order to promote bone-implant attachment (osseointegration). In this study, we investigate the influence of pure waterjet peening on a generated random metallic surface. The deformation of the substrate, the height distributions, material ratio curves of deformed surfaces, and 12 area roughness parameters were analyzed for different impact velocities, ranging from 100 m/s to 700 m/s, and different initial arithmetic mean heights (*Sa*), ranging from 0.62 μm to 1.88 μm. As the impact velocity increases, the height distribution becomes wider. The dispersion parameters *Sa* and *Sq*, extreme parameter *Sz*, and asymmetry parameter *Ssk* all reach their higher values at a higher impact velocity. The root mean square height *Sq* relates to surface energy where both cell adhesion and protein adsorption can be enhanced by a higher surface energy. The negative skewness *Ssk* surface obtained from the waterjet peening process corresponds to improved load bearing surface since most peaks can be worn away quickly, thereby providing a good contact condition for the implant and surrounding tissues. The material ratio curves obtained at different impact velocities demonstrate that higher impact velocity results in higher values of valley depth (*Svk*), which indicates a larger available surface area for cell adhesion, proliferation/differentiation. It is recommended that when describing the roughness in the context of cell adhesion research, the roughness parameters *Sq*, *Ssk*, *Svk* be reported as a minimum set.

1. Introduction

Successful osseointegration of orthopedic and dental implants is influenced by the available surface area of the implant, for which a larger contact area between the implant and the tissue surface is beneficial for improved mechanical cell adhesion compared to smooth surfaces (De Bruyn et al., 2017; Dorogoy et al., 2017; K. Shemtov-Yona and Rittel, 2015a, b). The contact area can be related to the surface roughness, and numerous reports mention that the surface roughness of titanium implants affects the osseointegration rate and biomechanical fixation (Larsson et al., 1996; Martin et al., 1995). Surface roughness can be divided into three levels, which are macro, micro and nano-sized topologies, based on the scale of the features (L. Le Guéhennec et al., 2007). The macro level is related to the implant geometry, and lie the range of millimeters to tens of microns. This level determines the early fixation and long-term mechanical stability of the prosthesis (Baggi et al., 2008; Quaranta et al., 2016). The micro level is defined for surface features, and lies in the range of 1–10 μm. A rough surface, with a moderate roughness of 1–2 μm, shows stronger bone responses than smoother or rougher surfaces (Albrektsson and Wennerberg, 2004). Living cells cannot be considered as smooth surfaces at separations inferior to 10–20 nm (Donoso et al., 2007). Consequently, a surface with nanometric level roughness is able to induce fast regeneration of the surrounding tissues due to its characteristic dimensions that are of the order of those of the cell (Moon et al., 2017).

Various surface modification technologies have been developed to modify titanium and other alloys used for biomedical applications (Liu et al., 2004). These methods can be classified into three main categories: mechanical, chemical and physical methods. Mechanical treatment, such as machining (Kunaporn and Hashish, 2000) and blasting (Lieblich et al., 2016), is mainly used to clean and roughen surfaces; chemical treatment, such as acid-etching and anodization (L Le Guéhennec et al., 2007), can improve the biocompatibility or bioactivity. Finally, physical methods, such as plasma spray (L Le Guéhennec et al., 2007) and ion implantation (Vardiman and Kant, 1982), play an important role in improving wear and corrosion resistance and other biological properties. For a more detailed discussion on surface modification technologies of titanium and its alloys, the reader is referred to (Liu et al., 2004; Mendonça et al., 2008).

Pure waterjet peening is one of the machining methods which was

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https://doi.org/10.1016/j.euromechsol.2018.03.022
Received 5 February 2018; Received in revised form 28 March 2018; Accepted 28 March 2018

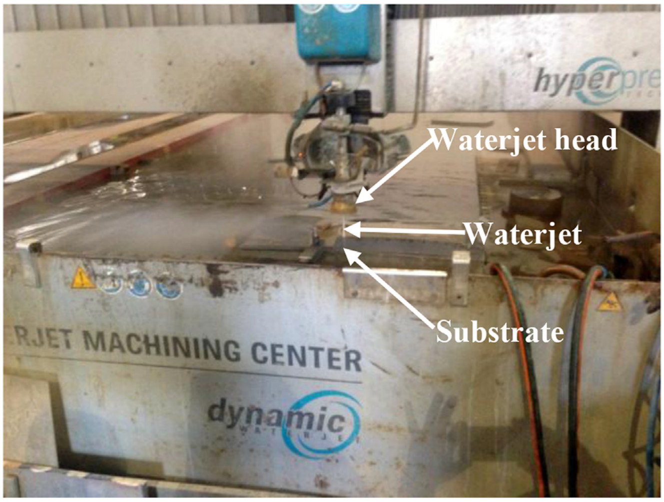

Fig. 1. A typical waterjet head used for peening.

initially proposed by VanKuiken Jr et al. (VanKuijen et al., 1995) and developed further by Hashish (1984) in the 1980s. A typical waterjet head is shown in Fig. 1. The water is ejected from a narrow orifice with a diameter of 0.08–0.8 mm at a high pressure ranging from 140 – 420 MPa, and becomes a high velocity jet than can strip, texture or peen the material surface (Xie and Rittel, 2017a). Several researchers (Arola and Mccain, 2000; Barriuso et al., 2011; Lieblich et al., 2016; Taylor, 1995) analyzed the feasibility and viability of pure waterjet peening for roughening the titanium alloy's surface and stated two main advantages of this method: the extremely high areal cover rate and environment friendliness.

In our previous work, the waterjet peening process was simplified as a droplet impact problem, thus a Coupled Eulerian Lagrangian (CEL) model was developed to investigate the single droplet impact problem (Xie and Rittel, 2017b). The initially flat surface assumption used in that simulation does not really reflect the physical reality, and may have been one of the reasons underlying a discrepancy between the numerical simulations and Arola' s (Arola and Mccain, 2000) experimental results. Consequently, in this study, we propose a method for generating random rough surfaces, using the finite element package Abaqus (Dassault Systèmes Simulia Corporation, 2014), in order to analyze the influence of the initial surface roughness on the resulting topography of titanium alloy surface after impingement.

The rough surface generation method is described in section 2. Computational details including parametric study, CEL model and surface roughness parameters, are given in section 3. In section 4 of this paper, the deformation profiles of the water flow, height parameters and functional parameters of deformed material surfaces are presented, followed by a discussion of the results in section 5.

2. Generation of a randomly rough surface for finite element analysis

The procedure to create a rough surface by editing the surface nodes of a meshed plate is as follows:

- Create a solid substrate (LENGTH × WIDTH × DEPTH).
- Set the element size to $(1/2)^n \times$ LENGTH, n being a positive integer. For convenience, the LENGTH equals to the WIDTH in this study, thus the surface has $(2^n + 1)^2$ nodes in total.
- Mesh the solid part, then obtain the initial mesh structure as shown in Fig. 2(a).
- Use the '**numpy.random.normal**' command of Python language to generate random numbers from a normal distribution. These numbers would set as the new heights of each surface nodes.
- Select all the surface nodes, and use a '**for**' loop command of Python language to modify the height of each surface node from the original one to the new value generated in the last step. The final mesh structure is displayed in Fig. 2(b).

This method is implemented in Abaqus (Dassault Systèmes Simulia Corporation, 2014). For random profiles, such as the resulting surface profile generated by using the method described above (Fig. 3(a)), although the shape cannot be determined by formula the statistics can. The profile can be replaced by a height distribution function as plotted in Fig. 3(b). There are many distribution forms to choose from, and in this study, the “most common” normal distribution is selected.

3. Computational details

3.1. Parametric study

As explained earlier (Xie and Rittel, 2017b), the waterjet actually contains countless droplets due to the atomization effect. Consequently, the same area of the substrate surface is repeatedly impacted by numerous droplets in a very short time duration. In this study, the discrete droplets impact representation is deliberately simplified as a continuous water flow with a cylindrical shape. In general, the sizes of droplets are distributed between some non-zero minimum diameter and a finite maximum diameter (Babinsky and Sojka, 2002). Here, the maximum droplet diameter of 500 μm (Minov et al., 2016) is assumed to be the diameter D_w of the cylinder. The droplet velocity depends on its maximum velocity at a given standoff distance of waterjet. According to the typical conditions of waterjet peening process (the average inlet pressure is 140–420 MPa), 7 classes of velocity ranging from 100 to 700 m/s, with an equal interval of 100 m/s, are defined for the parametric study (Xie and Rittel, 2017a).

3.2. Coupled Eulerian Lagrangian model

The CEL technique provided by Abaqus/Explicit (Dassault Systèmes Simulia Corporation, 2014) is particularly suitable for the large

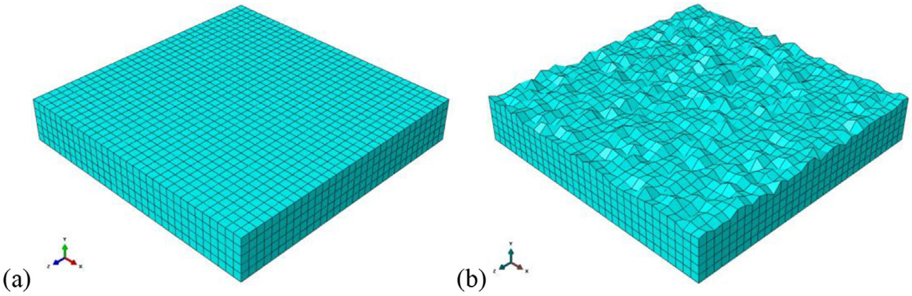

Fig. 2. Mesh structure before (a) and after (b) editing all the surface nodes' heights.