Optics and Lasers in Engineering 66 (2015) 258–268

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

# Introducing a new optimization tool for femtosecond laser-induced surface texturing on titanium, stainless steel, aluminum and copper

K.M. Tanvir Ahmmed [1], Edwin Jee Yang Ling [1], Phillip Servio, Anne-Marie Kietzig *

Department of Chemical Engineering, McGill University, 3610 University Street, Montreal, QC H3A 0C5 Canada

ARTICLE INFO

Article history:
Received 17 June 2014
Received in revised form
1 August 2014
Accepted 24 September 2014
Available online 20 October 2014

Keywords:
Femtosecond laser
Metal surface microstructures
Irradiation models
Optimization tool
Two-temperature model

ABSTRACT

The surface micro- and nano-scale features produced by femtosecond laser irradiation on titanium, stainless steel, aluminum and copper are reported in this work. Each observed surface microstructure, which was fabricated from a particular combination of four adjustable parameters, can be characterized by the fluence and pulses-per-spot (*F-PPS*) and accumulated fluence profile (*AFP*) models. By performing a wide screening of the experimental space, we have successfully mapped the evolution of micro-structures as a function of two variables per model. We have also shown that these two models, in conjunction with one another and the data that we have presented, can be used as an optimization tool for scientists and engineers to quickly fine-tune the laser processing settings necessary for a desired surface topography. In addition, the electron–phonon coupling strength and thermal conductivity have been identified as the material properties that have the largest influence over the achievable surface patterns on metallic substrates.



## 1. Introduction

Femtosecond (fs) laser technology has found uses in many areas, including spectroscopy [1], surgical procedures [2–4], pulsed laser deposition [5–7], the fabrication of coronary stents [8–10] and components of micro-electro-mechanical systems (MEMS) [11], to name a few. During laser micromachining, the ultra-short pulses of fs-lasers result in a minimal heat affected zone, which allows for high precision and damage-free material processing [12–15]. In addition to cutting and drilling, fs-lasers have been employed to produce micro- and nano-scale surface structures relevant in the fields of biomimicry [16–18], superhydrophobicity [18–20], color marking for counterfeit protection [21,22], and microfluidics [23,24]. Unfortunately, the exact formation mechanism (s) of such laser-induced surface topographies remain unknown due to the complexity of the laser machining process. Several researchers have put forward different laser ablation mechanisms based on physical models and molecular dynamics (MD) simulations [25–27]. While helpful in describing laser-material interactions, they do not account for numerous aspects of the micro-machining process that are poorly understood, such as the effect of plasma plume formation and expansion, nanoparticle shielding, oxide formation, incubation, optical property changes, self-organization, and the medium in which irradiation occurs.

Recent studies on metallic substrates have shown that the microstructures that are formed under laser irradiation can take the form of undulating grooves [28], bumps/spikes [17,29–38], holes [20,30,39–41], melt-like [41,42] and cauliflower-like [43] structures. In particular, Nayak and Gupta [36] examined the laser-induced surface topographies fabricated on titanium, stainless steel, aluminum and copper. Conical microstructures were observed on titanium and stainless steel, whose mean height and spacing varied with pulse fluence and the number of laser shots. On the other hand, the surface micro-cones that appeared on aluminum were less regular than those on titanium and stainless steel, while no micro-scale features were observed on copper under similar experimental conditions. Moradi et al. [30] classified the four types of microstructures they observed on stainless steel according to the laser power and the scanning speed, while Demir et al. [43] obtained five distinct surface morphologies on AZ31 Mg alloy by varying the pulse energy, repetition rate, scan speed and number of scans. In general, a large number of parameters may be adjusted during laser processing in order to attain a specific microstructure. As a result, optimizing the laser settings corresponding to a desired surface texture is a tedious and lengthy procedure due to the large breadth of the experimental space.

Although the micro- and nano-scale features observed on laser-irradiated metallic surfaces have been reported in literature, there is currently no systematic means of elucidating the effect of adjusting more than two independent processing parameters on the microstructures obtained. Furthermore, the morphology of the

* Corresponding author. Tel.: +1 514 398 3302.
E-mail address: anne.kietzig@mcgill.ca (A.-M. Kietzig).
[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.optlaseng.2014.09.017
0143-8166/

surface features obtained under similar experimental settings varies from metal to metal, and it is presently unclear how their material properties influence the laser-induced surface patterns. In this work, we have thoroughly investigated the numerous microstructures obtained on titanium, stainless steel, aluminum and copper by varying four processing parameters (power, scanning speed, sample position relative to the focal point, and line overlap) over a wide range of values. Using two different irradiation models, it is possible to systematically characterize the evolution of microstructures, some of which are reported here for the first time, to the best of our knowledge. These models, used in conjunction with one another, prove to be an essential tool for scientists and engineers to quickly fine-tune the processing parameters for surface micro-texturing via fs-laser irradiation. Our analysis also provides insight into the dominant microstructure formation mechanisms, as well as the importance of electron–phonon coupling strength and thermal conductivity on the morphology of surface micro-features.

## 2. Theoretical models

In order to impart a surface topography over an area larger than the beam spot size, laser pulses need to be overlapped in both horizontal ($x$) and vertical ($z$) directions. This is achieved by either manipulating the beam over the sample using multi-axis galvanometer scanners or displacing the sample using precise translation stages. In the models that follow, the laser beam, with pulse duration $\tau_p$ and repetition rate $f_p$, irradiates the sample in a raster scan pattern at a velocity $v$. The $1/e^2$ beam diameter $\omega_{theo}$ varies according to the position of the sample with respect to the focal point along the beam axis ($\Delta y$). The raster scan begins by overlapping pulses in the $x$-direction in displacements of $\Delta x = v/f_p$. This results in the etching of a horizontal line, whose effective ablated width $\omega_{eff}$ differs from $\omega_{theo}$ according to the material properties of the substrate and the medium in which the laser micromachining occurs. These horizontal lines are subsequently overlapped in vertical displacements that are a fraction of $\omega_{eff}$. Specifically, $\Delta z = (1-\varphi_{line})\omega_{eff}$, where $\varphi_{line}$ is known as the line overlap, and $0 < \varphi_{line} < 1$. In the following sections, two irradiation models that have recently been used in literature to classify surface texturing experiments are introduced.

### 2.1. Pulse fluence and pulses-per-spot (F-PPS)

The pulse fluence is calculated as the peak energy per pulse per unit area,

$$F = \frac{8P}{\pi\omega_{theo}^2 f_p} \tag{1}$$

where $P$ is the average, or measured, power of the laser beam. The $x$- and $z$-overlaps are taken into account by the pulses-per-spot ($PPS$):

$$PPS_{tot} = (PPS_x)\,(PPS_z) = \left(\frac{\omega_{theo}}{\Delta x}\right)\left(\frac{\omega_{theo}}{\Delta z}\right) \tag{2}$$

The $F$-$PPS$ model has commonly been used in literature to track the evolution of the surface topography of a material over a range of experimental parameters [28,35,40,41,44].

### 2.2. Accumulated fluence profile (AFP)

In their recent paper, Eichstädt et al. [45] developed an irradiation model that calculated the total fluence distribution over a reference area by summing individual Gaussian pulses displaced by $\Delta x$ and $\Delta z$. The fluence distribution of each pulse is given by

$$F_p(x,y,z) = \left(\frac{8P}{\pi\omega_{theo}^2 f_p}\right)\exp\left(-\frac{8(x^2+z^2)}{\omega_{theo}^2}\right) \tag{3}$$

Due to the ultra-short pulse duration in femtosecond laser micromachining, the sample displacement during the duration of the pulse is assumed to be negligible in comparison to the beam diameter, i.e. $\omega_{theo} \ll v\tau_p$. Summing successive pulses in the horizontal displacements of $\Delta x$ yields the accumulated pulse fluence profile, $F_{\Sigma pulse}$, which is the equivalent of engraving a horizontal line on a sample. Overlapping these horizontal lines in vertical displacements of $\Delta z$ gives the accumulated line profile, $F_{\Sigma line}$, which is the equivalent of etching a patch on the sample surface via a raster scanning pattern. The values of $\Delta x$ that arise from this work ensure that the spatial profile of $F_{\Sigma pulse}$ remains flat. On the other hand, choosing a low value of $\varphi_{line}$ will result in a wavy accumulated fluence profile for $F_{\Sigma line}$, as illustrated in Fig. 1a. From Fig. 1, it is clear that, as $\varphi_{line}$ decreases, $(F_{\Sigma line,max} - F_{\Sigma line,min})$ increases and $F_{\Sigma line,max}$ approaches $F_{\Sigma pulse,max}$ (Fig. 1a). Conversely, by increasing $\varphi_{line}$, the spatial profile of $F_{\Sigma line}$ flattens out, as in Fig. 1b. Here we consider a $F_{\Sigma line}$ profile as being flat when the relative difference between $F_{\Sigma line,max}$ and $F_{\Sigma line,min}$ is 1% or less. A detailed description of the model formulation can be found in Refs. [33,45]. Lehr and Kietzig [33] successfully correlated the two types of microstructures they obtained on laser-irradiated titanium to the pulse- and line-accumulated intensity profiles.

## 3. Experimental setup

Four metals were used in this study: titanium (Grade 2, 98.9% purity, McMaster-Carr), stainless steel 304 (McMaster-Carr), aluminum (Alloy 2024, McMaster-Carr), and copper (99.9% purity, McMaster-Carr), which were all polished with 600 and 1200 grit sandpaper ($R_a = 143$ nm) prior to experimentation. The samples were irradiated in air by an amplified Ti:Sapphire laser system (Coherent Libra) with a wavelength of 800 nm, a repetition rate $f_p$ of 10 kHz and a pulse duration $\tau_p$ of < 100 fs. The horizontally polarized Gaussian beam was focused to a $1/e^2$ theoretical beam diameter of 31 μm by a 100 mm converging lens. A variable

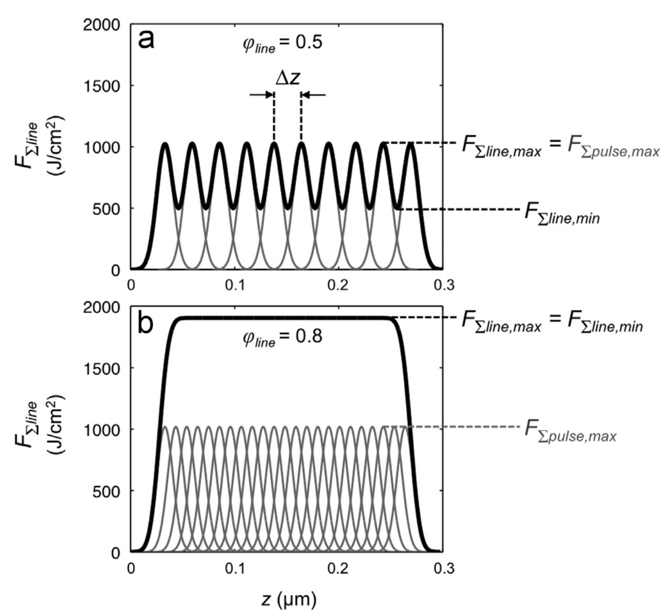


**Fig. 1.** Accumulated fluence profile for $P = 400$ mW, $v = 2$ mm/s, $\Delta y = 0$ mm and $\omega_{eff} = 52.5$ μm. (a) $\varphi_{line} = 0.5$ and (b) $\varphi_{line} = 0.8$.