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Controlling surface topography using pulsed laser micro structuring

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ABSTRACT

There is significant interest in controlling surface topography on metal parts including smoothing rough or wavy surfaces, adding aesthetic features, and creating functional structures. Pulsed laser micro structuring (PLμS) dynamically manipulates each pulse fluence during laser remelting to create a net, mass-neutral, lateral displacement of material several times greater than the melt pool diameter. This paper presents experimental investigations into specific process capabilities, example applications, and a novel phenomenological theory. The paper demonstrates how the resultant process can attenuate high-spatial-frequency roughness, correct mid-spatial-frequency error (*i.e.*, waviness), and create desirable surface topography with a single laser system.

1. Introduction

1.1. Surface structuring

It has long been known that the topography of a surface is critical in defining its esthetic and functional properties. A large body of literature is available on how surface topography contributes to reflection and light interaction, lubrication and wear, biological interaction, cracking and fatigue, and interfacial damping. More recently, new manufacturing techniques such as micro milling [1,2], precision diamond turning [3], high energy laser ablation [4], laser-induced plasma machining [5] and surface remelting [6,7] have been used to create surface topographies designed to control these properties. To date, surface structuring by remelting has been accomplished by two methods known to the authors: by modulating the incident laser power to cause periodic material displacement [6] and by using high intensity to form a keyhole in the melt pool and use this vapor pressure to push material while traversing. The former technique creates smaller aspect ratio features than the latter and is appropriate for periodic features whereas the latter method is typically used to create aperiodic structures such as pillars and walls. The present work is most closely related to previous work by Liu et al. [3] accomplished by continuous sinusoidal laser power variation and theorized that this caused a corresponding variation in the melt pool shape from concave at low power to convex at high power, therefore causing a change in the solidification direction: they posed that this change in the solidification direction resulted in a modified surface topography. The present work presents a unique approach for intentionally creating periodic structures by pulsed laser remelting and a novel theory for the acting principle behind the current work: periodic variation in laser energy causes corresponding variation in the thermocapillary flow that leads to alternating accumulation and depletion of material. This does not require that the shape of the melt pool change from concave to convex at the solidification point, only that the shape has a slight periodic variation. That is, a small periodic variation in the height of a convex melt pool will result in a wavy surface.

1.2. Pulsed laser micro structuring (PLμS)

The phenomenological theory behind PLμS is presented graphically in Fig. 1. During each laser pulse, the surface is heated, causing local melting and the development of a surface temperature gradient, which leads to thermocapillary flow and displacement of material at the free surface of the melt pool, followed by solidification (Fig. 1(a)). Everything else being held constant, the pulse energy density (*i.e.*, fluence) determines the extent of this displacement. By intentionally varying the fluence of each laser pulse, the local material displacement is varied, leading to the accumulation and depletion of material along the surface and resulting in residual surface topography (Fig. 1(b)). An example of a sinusoidal pattern created on a Ti6Al4V surface is shown in Fig. 1(c). This understanding of thermocapillary flow builds on prior experimental and analytical investigations of pulsed laser remelting for smoothing [8–10].

More complex examples of PLμS are shown in Fig. 2. Fig. 2(a) shows the creation of an intricate decorative pattern with fine micro-scale detail on 430 stainless steel. Fig. 2(b) shows a larger scale application where the shoulder of a friction stir welding (FSW) tool, made of H13 tool steel, has been functionalized with a spiral structure that has a wavelength of approximately 800 μm at the tool's outer diameter (OD). These exemplify the complexity, selectivity, and scalability of the structures created through PLμS. The parameters used to create these surface structures are given in Table 1 along with the experimental parameters used in the fundamental studies presented in the following sections.

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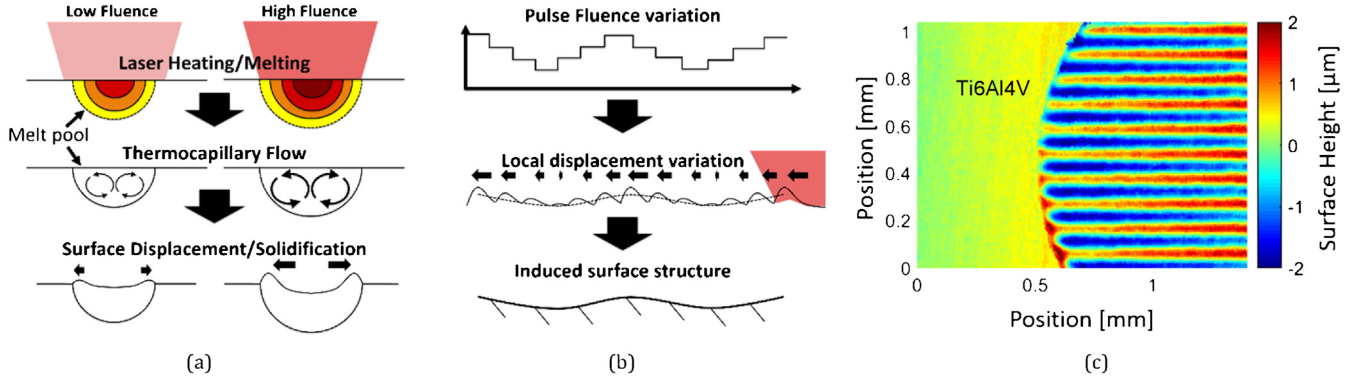

Fig. 1. A graphical representation of pulsed laser micro structuring (PLµS): (a) the phenomena occurring during the melting of a single laser spot including the creation of a temperature gradient in the melt pool, surface-tension driven thermocapillary flow, and resulting surface displacement; (b) controlled variation of the fluence between each laser pulse, leading to variations in local displacement; (c) induced surface structure on Ti6Al4V.

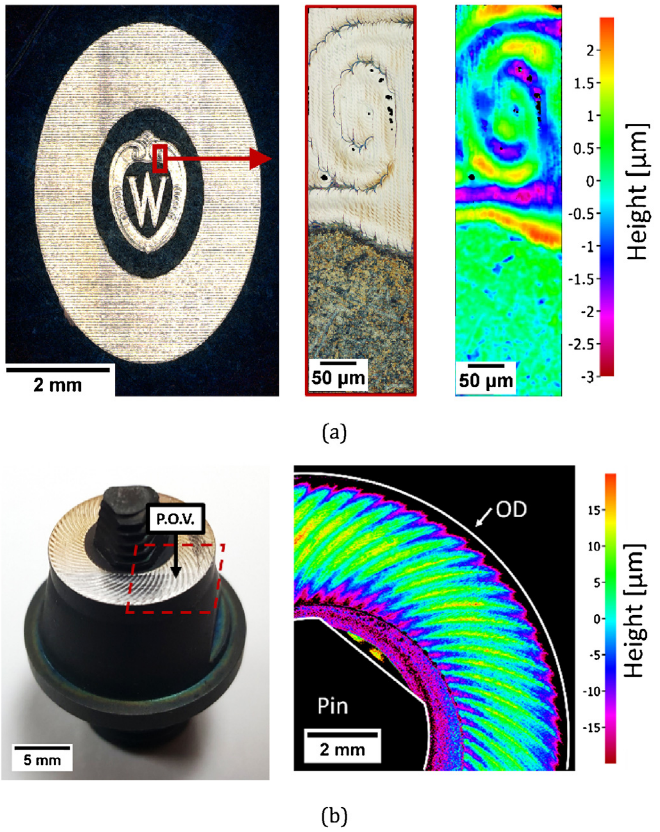

Fig. 2. Examples of pulsed laser micro structuring (PLµS): (a) a decorative application with micro-scale features (430 stainless steel), and (b) an engineered surface (H13 tool steel) on the shoulder of a friction stir welding (FSW) tool.

Table 1
Conditions used for laser structuring experiments.

	Condition A	Condition B
Laser spot diameter (µm)	30	100
Pulse Power (W)	10	100
Spot overlap (µm)	5	15
Scan step-over (µm)	5	15
Pulse duration (µs)	5–8	5–8
Fluence (J/cm^2)	7–11	6–10
Experiments performed with these conditions	All other experiments	FSW tool (Fig. 2(b))
Workpiece material	430 stainless steel, Ti-6Al-4V	H13 tool steel

2. Experimental setup

The laser used was a 1070 nm wavelength, continuous wave (200 W maximum), diode-pumped, fiber laser (SPI Model SP-200C-W-S6-A-B). The laser is pulsed by turning the diodes on/off with an external control card (LasX Industries, Proton control board). A scanhead (ScanLab, HurryscanII) was used to direct the laser across the surface, and a vacuum chamber with reduced air pressure was used to minimize oxidation during processing (P_{Air} = 0.08 Torr). The experimental parameters used are given in Table 1. Condition A (30-µm-diameter spot) was used for all the fundamental process studies on Ti6Al4V, as well as the examples shown in Figs. 1(c) and 2(a). Condition B used a larger laser spot to create the surface topography in Fig. 2b.

Fig. 3 illustrates how a linear scan path can be used to create a complex structure through controlling the pulse duration (*i.e.*, fluence) along each successive scan path by relating the gray-scale values in the image to pulse duration values. The laser path was a series of one-directional scans in the y-direction (vertical direction) for all the surfaces shown in this paper. No complex scan path planning was used. A gray-scale image (Fig. 3(a)) was used to define the fluence for each pulse along the scan path where the fluence was defined by the pulse duration. Pulse duration, t_p, was defined for each laser spot location in the image by setting true black to define the laser as off ($t_p = 0$ µs), one value above true black as a minimum pulse duration value (15% Duty Cycle: $t_p = 5$ µs), and full white as the maximum pulse duration (25% Duty Cycle: $t_p = 8$ µs). Matrices of these gray values were created in Matlab and saved as images. Fig. 3 shows a "fluence control map" that is similar to the one used to create the structure in Fig. 1(c).

Previous work in laser structuring has focused on continuous sinusoidal variation of laser power [3]. Since PLµS is a pulsed process, a discretized approximation of a control function is defined. First, sinusoidal control was explored with wavelengths of 50 µm, 100 µm, and 200 µm to compare the outcome with previous literature. Then, the present work additionally explores the impact of using non-sinusoidal control functions by applying triangle, "sawtooth," and "reverse sawtooth" waveforms. This is

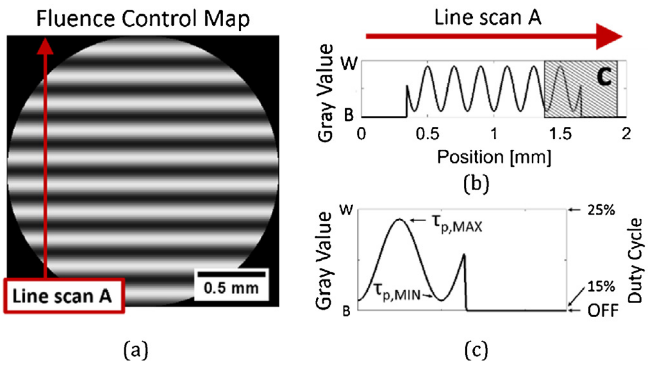

Fig. 3. Illustration of (a) a PLµS fluence control map, (b) the grayscale variation along a single line scan, and (c) the relationship between the grayscale values and pulse control.

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