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# Improving surface finish in pulsed laser micro polishing using thermocapillary flow

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ABSTRACT

Thermocapillary flows can be generated in pulsed laser micro polishing by using longer melt durations, significantly reducing surface roughness at the expense of creating residual high spatial frequency process features. However, polishing with short melt durations, with no thermocapillary flows, effectively smoothens high spatial frequency surface features. This paper presents a two-pass polishing process in which the first pass takes advantage of *thermocapillary flows* in significantly reducing the surface roughness, and the second pass removes the residual process features. Experimental results of polishing micro end milled Ti6Al4V surfaces are presented that indicate 72% improvement in average surface roughness.

## 1. Introduction

Pulsed laser micro polishing (PLμP) is a non-contact surface smoothing process suitable for metallic parts of micro/meso scales, where conventional polishing methods are unproductive and/or uneconomic. In PLμP, laser pulses irradiate the surface, and each pulse results in melting of the surface asperities in a small area. These molten surface asperities, which are the regions of high surface tension, transition towards a state of low surface tension before resolidification, producing a smoother surface.

Continuous-wave (CW) laser polishing has been investigated on macro-scale metal parts [1,2] with positive results. However, this can result in melt-depths and heat affected depths of 100s of microns [3]. This may not be suitable for devices with dimensions measured in 10s to 100s of microns. Pulsed laser polishing enables better control of melt depth ($<6$ μm) and heat affected zone ($<10$ μm) [4]. A combined CW and pulse laser polishing as a two-step process was investigated on tool steel, stainless steel, cobalt–chromium alloys and titanium and was shown to improve the surface finish by a factor of 5–10 [3,5,6]. Brinksmeier et al. experimentally compared this two-step polishing process and abrasive flow machining by comparing the surface finish achieved on structured steel molds with a 150° V-groove [7]. They reported significant rounding of the edges and the bottom of the grove as compared to that achieved via laser polishing showing the versatility of the process. Yasa et al. [8] used laser re-melting as a finishing step to improve the surface quality of parts manufactured using selective laser melting (SLM) and have reported an improvement of 90% (from 12 μm to 1.5 μm) of average roughness, $R_a$. More recently, researchers [9,10] have investigated the influence of laser pulse duration on laser micro polishing and concluded that longer pulse durations can successfully polish longer spatial wavelengths.

The achievable surface finish in PLμP is significantly dependent on the melt duration and the surface tension forces. Perry et al. [9,11] observed that at short melt durations (usually $<1$ μs), the melt pool dynamics can be modelled as oscillations of stationary capillary waves that damp out due to the viscosity of the melt. Vadali et al. [4] recently showed that significant improvements in the surface finish can be obtained using longer melt durations (via longer pulse durations) that result in thermocapillary flows; however, these flows leave residual high spatial frequency processing features on the surface. A novel two-pass PLμP method will be presented in this paper in which the first pass takes advantage of thermocapillary flows in significantly reducing the surface roughness and the second pass, which avoids thermocapillary flows, removes the residual process features to further improve the surface finish. An analysis of the operating regimes for PLμP will be presented, along with experimental results on micro end milled Ti6Al4V alloy and detailed analysis.

## 2. Capillary and thermocapillary regimes in PLμP

Thermocapillary flow or Marangoni flow [12] (Fig. 1) is a result of surface tension being a function of temperature and temperature gradients existing in melt pools. Titanium alloy Ti6Al4V [13] has a negative temperature gradient of surface tension. The melt pools created during PLμP experience the highest temperatures at their center. The result for Ti6Al4V is that the regions of highest surface tension are at the edge of the melt pool with a driving force towards the outer edge. This flow along the surface of the melt pool results in upwelling of material as resolidification occurs. There are two distinct regimes of operation in PLμP, the *thermocapillary regime* and the *capillary regime*, based on whether surface tension gradient driven thermocapillary flows are dominant or negligible. The PLμP results under these two regimes differ significantly.

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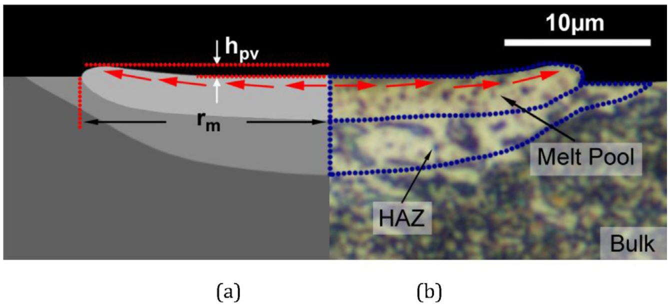

(a) (b)

**Fig. 1.** Thermocapillary flow towards the edge of the melt pool in PLμP: (a) illustrative schematic of thermocapillary flow; (b) micro cross section image of a line scan in thermocapillary regime.

Thermocapillary flows are negligible when melt durations are short and the temperature gradient is relatively small. In the *capillary regime*, the molten rough surface features that are regions of relatively high surface tension oscillate as stationary capillary waves; hence, the name. The amplitudes of these oscillations, i.e., the heights of roughness features, damp out due to the viscosity of the molten metal before resolidification, resulting in a smoother surface [9,11].

These authors have previously shown that in the capillary regime the amplitudes of the surface roughness features after resolidification can be analysed using spatial Fourier analysis, and can be approximated as follows [14]:

$$\zeta(f_x, f_y)_{\mathrm{polished}} = \zeta(f_x, f_y)_{\mathrm{unpolished}} e^{-[(f_x/f_{\mathrm{cr}})^2 + (f_y/f_{\mathrm{cr}})^2]} \quad (1)$$

where $\zeta(f_x, f_y)$ is the amplitude of the spatial frequency component at $(f_x, f_y)$ and $f_{\mathrm{cr}}$ is the critical frequency. The critical frequency is a function of the melt duration ($t_{\mathrm{m}}$) and the material properties (density, $\rho$ and dynamic viscosity, $\mu$) [9,11]:

$$f_{\mathrm{cr}} = \left(\frac{\rho}{8\pi^2 \mu t_{\mathrm{m}}}\right)^{1/2} \quad (2)$$

PLμP in the *capillary regime* is effective in smoothing spatial frequency features above the critical frequency, but does not have a significant effect on low frequency or long wavelength features. On the other hand, PLμP at long melt durations in the thermocapillary flow regime not only reduces the amplitudes of high spatial frequency asperities features, but also significantly reduces the amplitudes of lower spatial frequency asperities. This is illustrated by the surface height data plots in Fig. 2 and line profile data plots in Fig. 3. Fig. 2(b) shows PLμP results for a micro end milled surface in the thermocapillary regime in which a 50% reduction in average surface roughness $S_a$ (for an evaluation area of ~0.09 mm$^2$) [15,16] was obtained, while Fig. 2(c) shows PLμP results in the capillary regime in which only a 12% reduction in $S_a$ was obtained because only higher spatial frequency features were removed.

The stationary capillary flow model in Eqs. (1) and (2) is not applicable in the thermocapillary regime. A two-dimensional, numerical, axisymmetric, finite element method model (COMSOL Multiphysics) that couples heat transfer and fluid flow processes was developed to understand the melt pool dynamics. The effects of process parameters such as incident power, spot diameter, laser pulse width, material properties, etc. on melt depth, melt duration and evolution of the surface under thermocapillary flows were studied. Temperature-dependent material properties were included in the model.

In spite of significant surface roughness reduction in the thermocapillary regime, a circular feature is introduced onto the surface by each laser pulse because of the flow of liquid metal to the edges in materials such as Ti6Al4V. Due to overlapping pulses, a surface ripple is created that can be seen in Fig. 2(b), which has a spatial frequency equal to the number of pulses per mm. This

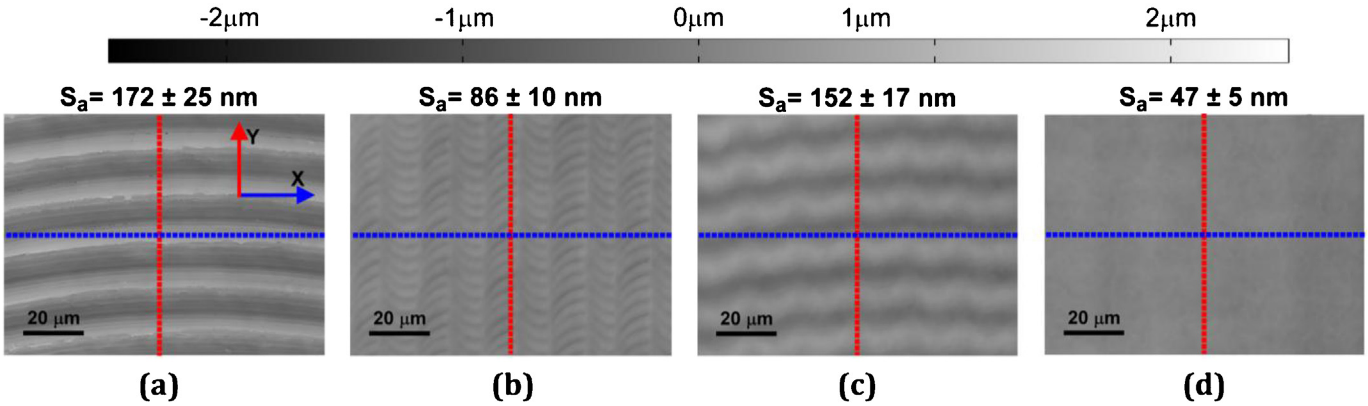

**Fig. 2.** Surface height data: (a) unpolished micro end milled surface; (b) surface polished in thermocapillary PLμP regime; (c) surface polished in capillary PLμP regime; (d) surface polished using two pass PLμP.

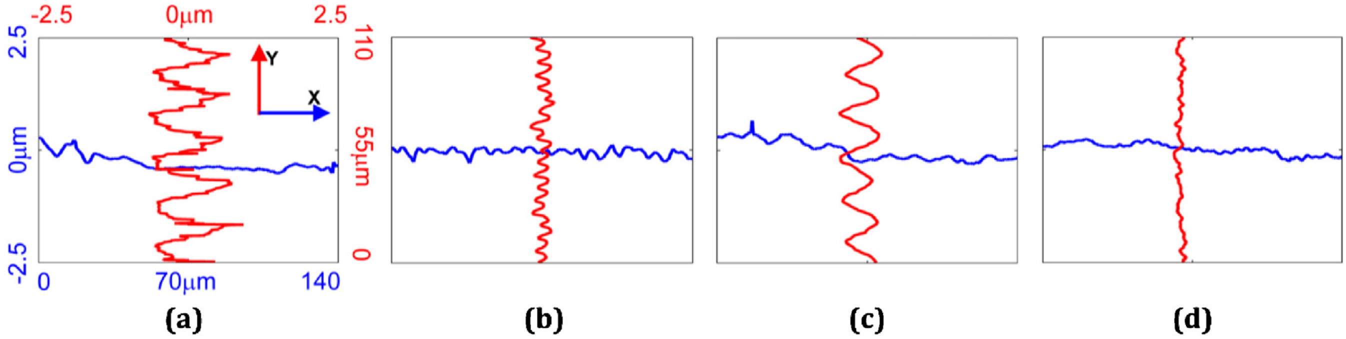

**Fig. 3.** Line profile data extracted from Fig. 2: (a) unpolished micro end milled surface; (b) surface polished in thermocapillary PLμP regime; (c) surface polished in capillary PLμP regime; (d) surface polished using two pass PLμP.