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# Fundamental study of the bulge structure generated in laser polishing process

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ABSTRACT

Laser polishing is an innovative part-finishing process to reduce the surface roughness by melting a thin layer of material on the part surface. The polished surface quality is influenced by many factors including initial surface condition, properties of material, laser power, scan speed, focal offset, beam shape, percentage of overlap, etc. In addition to removing the original asperities, the laser polishing process may also introduce new asperities including bulges, ripples, undercuts, etc. In this paper, a fundamental study is carried out on Ti-6Al-4 V alloy slabs to investigate the formation of bulge structure and the influence of processing parameters (the laser power, scan speed, focal offset and successive track displacement) on the bulge structure through parametric analyses. The formation of bulge structure is mainly caused by the phase transition in the heat-affected zone and the mass transport of the fluid flow in melting pool. The parameters of the laser power, scan speed and focal offset have significant influences on the width and depth of polished tracks, the amplitude of bulge structures and the relative volume expansion by the bulge structures. Two different melting modes and a maximum track width can be found in the parametric study of focal offset. The scan speed has a significant influence on the relative volume expansion at low speeds. By reducing the successive track displacement, the overlapped bulge amplitude can be reduced rapidly, but the finer solidification-induced surface structure would get intensified.



## 1. Introduction

Recent years, additive manufacturing (AM) has become an important and promising technology especially for the fabrication of aero industrial parts [1–3], because AM processes can achieve highly complex 3D geometries and the very low material wastage, compared with the traditional subtractive manufacturing processes. However, AM fabricated parts usually have a poor surface quality, which could lead to unacceptable tolerance and increased friction, and potentially become a source of fatigue crack initiation [4–6]. So, the post-processing of AM fabricated parts, especially surface polishing, is essentially required in the actual applications. Recently, laser polishing is a promising and competent polishing process [7]. And it has the following obvious advantages over some traditional polishing processes (e.g. abrasive polishing and electro-chemical polishing): non-contact, no material removal, no pollution, high automation, selective processing and less polishing times [8]. Laser polishing, as a physical process, involves creating a thin molten layer on the substrate with laser radiation, and the surface asperities would be reduced or eliminated by the capillary or thermo-capillary effect of molten material.

Many studies on laser polishing processes have been reported [4,9–26], and have shown promising results. However, a majority of the available research is based on the statistical Design of Experiment methods, and few research was concerned with the fundamental study of the laser polishing processes. Ramos et al. [4], studied the laser macro polishing process [8] on the selective laser sintering (SLS) fabricated parts, and identified two different laser polishing regimes: surface shallow melting (SSM) and surface over melting (SOM). In the regime of SSM, the thickness of the melted layer is less than the peak-to-valley height of the typical surface asperities, and the molten material flows from the peaks to the local valleys under the capillary pressure. In the regime of SOM, the thickness of the melted layer is greater than the peak-to-valley height of asperities, then the original surface topography may completely disappear and a continuously moving melting pool is created. In the research of laser micro polishing [8] with the pulsed laser radiation, two polishing regimes, similar to SSM and SOM, were recognized as the capillary regime and the thermo-capillary regime [27,28]. The capillary regime is performed with short laser pulses (e.g. hundreds of nanosecond) and the thermo-capillary regime with relatively longer laser pulses (e.g. several microsecond).

In the experimental studies of laser polishing processes [14,16,29], the SOM regime and thermocapillary regime, which have a relatively

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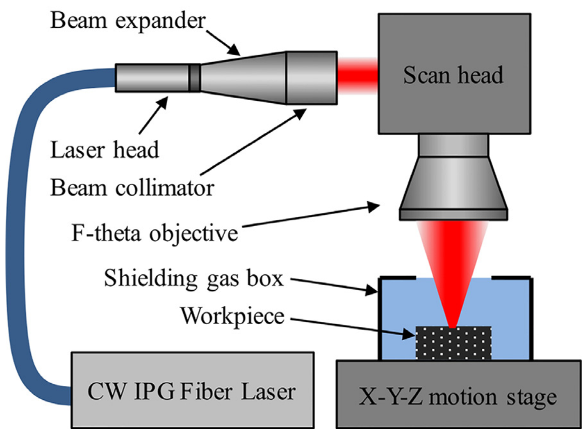


**Fig. 1.** The experimental setup for the laser macro polishing study.

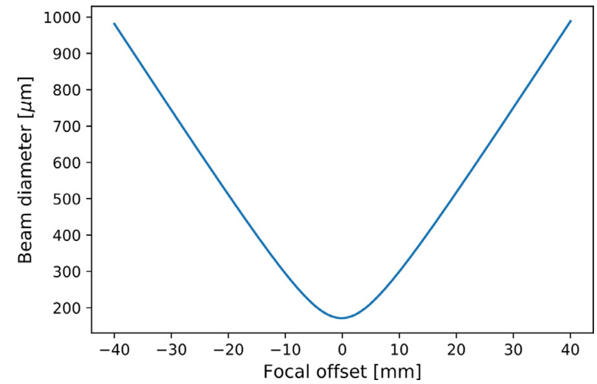


**Fig. 2.** The relation between the laser beam diameter and the focal offset.

**Table 1**
The parameter values of the laser power, scan speed and focal offset in the single-line polishing tests.

| Studied parameters | Parameter values |
|---|---|
| Laser power (W) | 150, 200, 250, 300, 350, 400, 450, 500 |
| Scan speed (mm/s) | 100, 200, 300, 400, 500, 600, 700, 800 |
| Focal offset (mm) | 4, 8, 12, 16, 20, 24, 28, 32 |

higher energy input, exhibit a better polishing capability than the SSM regime and the capillary regime. However, the SOM and thermocapillary regimes can also bring some drawbacks. The polishing process in the SOM and thermocapillary regimes may eliminate or distort some desired surface microstructures or micro-feature geometries. And the material bulging phenomenon is usually resulted in along the polishing tracks [14,29]. In the study by Nusser et al. [30], the polishing-induced bulge was identified as one of five possible material-/process-induced surface structures in laser macro polishing processes, which are ripples, undercuts, bulges, step structures and martensite needles. And they may have some impacts on the final polished surface finish. However, it has not been reported of any specific studies on the bulge structures produced by laser polished tracks so far. Therefore, we hope in this work to conduct an experimental study on the bulging phenomenon in the laser macro polishing processes under the SOM regime.

In the research of this paper, the experimental study of the bulge structures in the laser macro polishing processes was conducted on the Ti-6Al-4 V alloy substrates which are an important material in the aviation manufacturing. First the bulge structure on a single polishing track is examined, and parametric studies were then carried out to study the influence of laser processing parameters on the bulges structures. The possible reasons of the formation of bulge were analyzed. Furthermore, the reduction and elimination of bulge structure by the polished-tracks overlapping was studied.

## 2. Experimental procedure

### 2.1. Material and experimental setup

The Ti-6Al-4 V alloy substrates of the thickness 5 mm were provided in this study.

The basic experimental setup is illustrated in Fig. 1. The laser applied is a 1070-nm 1000-W continuous wave (CW) fiber laser (IPG Lasers, Model: YLR-1000-MM-WC-T11). The CW laser beam is directed into a scan head (ScanLab, HurryScan 30 mm) allowing for high-speed two-dimensional scanning, and focused by an F-theta lens with a focal length of 300 mm. The workpiece is put in a shielding gas chamber filled with argon gas flow, which has a top opening for the incoming laser beam and is fixed on an X-Y-Z motion stage (Aerotech, Model: ATS 10,060-H-M-80P-NC), which provides a motion resolution of 1 μm in the X and Y directions and a 0.1 μm resolution in the Z direction.

The sample surface topographies before and after the polishing process were measured with a Wyko NT9100 white light interferometer having a 1 nm height measurement resolution in the VSI mode.

### 2.2. Research methodology and procedure

Prior to the laser polishing experiments, the prepared Ti-6Al-4 V substrates were mechanically polished by a sand paper, with a resulted surface roughness of 0.1 μm in *R*a. As stated in Ref [30], the final surface roughness after laser polishing does not only contain the remains of the initial surface roughness, but also contains new roughness induced by the laser polishing process. Since the subject of this research is the bulge structures formed during the laser macro polishing processes, the influence of the initial surface condition on the final surface finish should be reduced to a minimum level.

The experimental study of the bulge phenomenon in laser polishing processes comprises two major steps: single-line polishing tests and the overlapped multi-line polishing tests. The objective of single-line polishing tests is to analyze the influences of laser polishing parameters on the bulge structures, and the parametric-studied polishing parameters includes the laser power, the laser scan speed and the focal offset distance. Here the adjustment of the focal offset distance corresponds to the change of the laser beam diameter, which is shown in Fig. 2 as a function of the focal offset distance, where the focal offset of zeros means the location of focal plane, the focal offset of negative values means the location inside the focal length and the positive values correspond to the location outside the focal length.

These three parameters work together to influence the induced bulge structure. However, the parametric study in this step is carried out based on the way of the change of one-factor-at-a-time. In the experiment, a baseline of laser polishing parameter was set as the laser power of 400 W, the scan speed of 200 mm/s, and the focal offset distance of 20 mm. When one parameter is studied the other two parameters keep as the base values. In detail, the studied values of the three parameters are listed in Table. 1. And the laser beam diameters corresponding to the listed focal offsets are 195, 256, 335, 421, 511, 604, 697 and 791 μm, respectively.

After the single-line polishing tests, the samples were examined and measured with an optical microscope and optical profiler. Then the samples were sectioned, polished, and etched, and the etched cross-section of samples were examined under the optical microscope.

In the second step of overlapped multi-line polishing tests, the polishing process was carried out line by line successively and the polishing