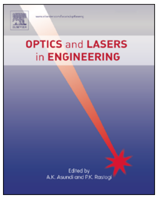
Optics and Lasers in Engineering 78 (2016) 55–63

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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



Porous microstructures induced by picosecond laser scanning irradiation on stainless steel surface

Bin Liu, Gedong Jiang, Wenjun Wang*, Xuesong Mei, Kedian Wang, Jianlei Cui, Jiuhong Wang

State Key Laboratory for Manufacturing System Engineering, Xi'an Jiaotong University, Xi'an 710054, China

ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form
2 September 2015
Accepted 2 October 2015

Keywords:
Porous surface
Micropores
Laser surface texturing
Picosecond laser

ABSTRACT

A study of porous surfaces having micropores significantly smaller than laser spot on the stainless steel 304L sample surface induced by a picosecond regenerative amplified laser, operating at 1064 nm, is presented. Variations in the interaction regime of picosecond laser pulses with stainless steel surfaces at peak irradiation fluences($F_{pk}=0.378$–$4.496\ \mathrm{J/cm^2}$) with scanning speeds($v=125$–$1000\ \mu\mathrm{m/s}$) and scan line spacings($s=0$–$50\ \mu\mathrm{m}$) have been observed and thoroughly investigated. It is observed that interactions within these parameters allows for the generation of well-defined structured surfaces. To investigate the formation mechanism of sub-focus micropores, the influence of key processing parameters has been analyzed using a pre-designed laser pulse scanning layout. Appearances of sub-focus ripples and micropores with the variation of laser peak fluence, scanning speed and scan line spacing have been observed. The dependencies of surface structures on these interaction parameters have been preliminarily verified. With the help of the experimental results obtained, interaction parameters for fabrication of large area homogeneous porous structures with the feature sizes in the range of 3–15 μm are determined.

1. Introduction

With the emergence of the ultrashort laser in the 1990s, ultrashort laser micromachining has been heralded in recent years as a new technique for micro/nanostructure fabrication [1–4]. From their initial demonstration, ultrashort lasers have been shown to be an easy one-step processing method for virtually all kinds of materials, with utilization of sub-micron spot sizes. In addition, ultrashort lasers can provide greater flexibility for ablation processing methods [5–8].

In recent years, surface structuring with ultrashort lasers are of growing interest because of the capability to control the optical, mechanical, wetting, chemical, biological, and other properties of a solid surface [2]. Many approaches on metallic substrates have shown that microstructures formed under ultrashort laser irradiation can take the form of nanoripples, grooves and even pores. Hondaet al. [9] obtained nanoripples, nanopores and grooves by changing the femtosecond laser fluence and the number of pulses irradiated at a fixed position, and showed us an evolution of structures from periodic nanostructures to periodic microstructures. Our previous work [10] also has explained the origin of pores by investigating formation of nano/micropores by changing laser pulse number and fluence irradiation of multi-pulse picosecond laser at a fixed position, and revealed the evolution of the micropores through a comparison of experimental results. However, in order to attain homogeneous porous structures over a large area for various applications, a large number of laser processing parameters are required to be adjusted due to the large breadth of the experimental space. When porous structures are formed by laser pulse scanning, the cumulative effect of laser pulse energy irradiated on the material surface is directly dependent upon the scanning speed and line overlap, rather than on the number of pulses irradiated on a fixed point. Bao et al. [11] used picosecond laser to ablate microgrooves accompanying with the cavities, mastoids and the low spatial frequency picosecond laser-induced periodic surface structures (LSFLs). By varying the scanning interval and the scanning speed, they change the wetting behaviors of the AISI 304 stainless steel surface. Kam et al. [12] used low pulse energy and high repetition rate of femtosecond laser pulses scanning on AISI 316L stainless steel surface to demonstrate controllable wettability by a wide range of liquid contact angles. They found that the scan speed, except as the fluence, played a key role in controlling surface wettability by changing micro-cone number density (or the size of micro-cone

---

* Corresponding author.
E-mail address: wenjunwang@mail.xjtu.edu.cn (W. Wang).

http://dx.doi.org/10.1016/j.optlaseng.2015.10.003

microstructures). Both above studies show us the ultrafast laser large-area manufacture of surface microstructures and their applications in surface wettability, but more experimental and theoretical analyses on surface microstructuring are need to help further investigate the laws governing the development of microstructures.

In this paper, we describes a reproducible method for achieving porous surfaces with a high reproducibility over a large area through investigation of the evolution of surface topography. In the investigations described below, emphasis is placed on the subfocal ripples and micropores on the surface of a stainless steel 304L target by laser pulse scanning on a predesigned path. All scanning paths are triangular to allow variation of three dominating processing parameters: peak fluence, scanning speed and scan-line spacing (i.e. the distance between successive scan lines, or scan line overlap). A homogeneous structured surface with varying types and sizes of microstructures is obtained by controlling these three parameters. The experimental quantitative analysis of laser parameters for surface microstructuring is demonstrated to further investigate the change rule of microstructures. Finally, based on the acquired experimental data, preparation of sub-spot porous structures homogeneously distributed on a large area is demonstrated.

2. Experimental

A High-Q picosecond laser system based on pulse regenerative amplification is used. The laser system delivers ~0.3 mJ per pulse at 1 kHz repetition rate at a wavelength of 1064 nm, 10 ps pulse length. The power density distribution of the laser beam is Gaussian. The experimental setup is depicted in Fig. 1. The laser pulse energy is adjusted by using a combination of a half-wave plate and a linear polarizer. A pyroelectric detector is used to monitor the laser power in real time with conjunction with a beam splitter in the primary laser path. The number of pulses is programmable using an electromechanical shutter. The laser beam is focused and normally incident onto the surface of sample using an f-theta lens ($f = 150$ mm). The focused beam radius ω_0 is calculated to be ~45 μm based on the experimental difference between irradiated laser power and the diameter of laser ablated crater [13]. A motorized *xyz* stage controlled by computer is used for precise positioning of the samples. All the laser ablation experiments are performed in air.

The surface of the stainless steel 304 initially has a typical silver–gray metallic color before laser irradiation. Firstly, the surface of the steel sample was mechanically polished with sandpaper with a grit size of 2500 grooves/mm and was subsequently fine polished with Al_2O_3 powder having an average particle size of ~1 μm. The surface roughness R_a of the polished stainless steel is about 200 nm as measured by a Profile-imaging-system(Ambios XP-2). After the polishing process, the sample was cleaned in an ultrasonic bath firstly of acetone for 10 min to remove oily contaminants and subsequently by alcohol for 10 min. Finally, the sample was rinsed with distilled water and was dried by nitrogen.

After the pre-processing, the sample surfaces were irradiated by series of laser pulses at 1064 nm wavelength and at 1 kHz repetition rate: a different fixed peak fluence ($F_{pk} = 0.378$–4.496 J/cm^2) was attained by adjusting the laser power, and the designed scanning path was applied with varying scanning speeds ($v = 125$–1000 μm/s) and scan-line spacings ($s = 0$–50 μm). These three parameters above directly affect the accumulated absorption of laser pulse energy on material surface. The fabrication of a structured area in a raster scan requires overlapping of pulses in both horizontal and vertical directions. The scanning speed determines the overlap of pulses (φ_{pulse}) when the laser etches the sample in the scanning direction. The scan-line spacing also determines the vertical overlap, also referred to as the line overlap(φ_{line}) [1]. Each triangular scanning path allows us to synchronously change two processing parameters (pulse overlap φ_{pulse} and line overlap φ_{line}) at the specific peak fluence, due to the small angle between the contiguous lines, as shown in Fig. 2(a).

After laser irradiation, the ablated surfaces of the samples were inspected with a Scanning Electron Microscope (SEM: Hitachi SU-8010). And the full-view SEM-images of corresponding experiments are demonstrated with labeled corresponding peak fluences, as shown in Fig. 2(b).

3. Results and discussions

3.1. Appearance of surface structures

A series of surface morphologies (Fig. 2(b)), obtained after ps-laser beam scanning and structuring, illustrates the evolution of surface structures as a function of the laser parameters. From the above, three distinctive surface structure regions (nanoripples, microgrooves and micropores) are identified, as shown in Fig. 3.

Laser-induced periodic surface structures (LIPSS), also termed ripples or nanoripples, are periodic nanostructures constituted of alternate crests and troughs, as shown in Fig. 3(a). In terms of their periodicity, nanoripples can be divided into low-spatial-frequency LIPSS (LSFL) and high spatial-frequency LIPSS (HSFL). LSFL have spatial periods between ~0.6λ and λ and are most likely produced by interaction between the incident laser beam and the surface

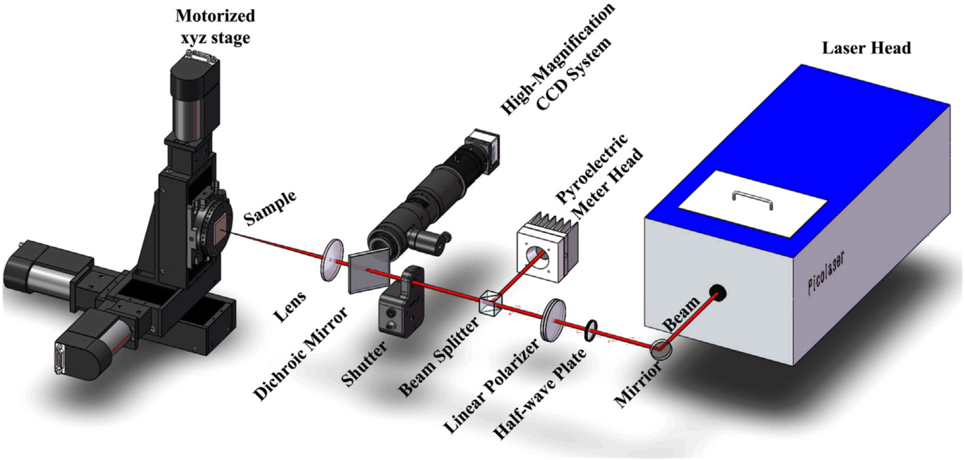


Fig. 1. Experimental device.