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Periodic surface structures on titanium self-organized upon double femtosecond pulse exposures

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ABSTRACT

Laser induced periodic surface structures (LIPSS) self-organized on Ti surface after irradiations by femtosecond laser beam composed by double pulses with a fixed time delay of 160 fs. The fluence of the first pulse (F_{PP}), responsible for surface plasma formation, was varied in the range 10–50 mJ cm^{-2} and always kept below the LIPSS formation threshold fluence (F_{LIPSS}) on Ti for 50-single-shots exposure. The fluence of the delayed pulse (F_{LP}), responsible for LIPSS self-organization, was varied in the range 60–150 mJ cm^{-2} and always kept above F_{LIPSS}. Regardless the specific fluence F_{LP} of the delayed pulse, the interspace of the grating structures increases with the increase of F_{PP}, that is an increase of the surface plasma density. This tendency suggests that a variation of the surface plasma density, due to a variation of F_{PP}, actually leads to a modification of the grating features. Moreover, we observed that the LIPSS periodicities after double pulse exposures are in quite good agreement with data on LIPSS periodicities after single 160 fs pulse irradiations on Ti surface and with the curve predicted by the parametric decay model. This experimental result suggests that the preformed plasma might be produced in the rising edge of the temporal profile of the laser pulse.

1. Introduction

Laser induced periodic surface structures are nowadays of great interests in many application fields, thanks to the current possibility of large area laser processing in different geometries of many kinds of materials [1–3]. Therefore, it appears clear the necessity to possess a handy model, which allows foreseeing directly LIPSS interspaces from key process parameters of the laser, such as, for instance, the laser fluence and number of pulses. It is well known that under irradiation of linear polarized femtosecond laser pulses, in a range of fluences determined by the material properties, grating structures with spatial periodicity slightly smaller than the laser wavelength are self-organized and oriented perpendicular to the laser polarization direction [4–8]. Nevertheless, the physical mechanisms at the base of LIPSS formation are still highly debated in literature and many models have been proposed [9–19]. In this frame, a parametric decay model has been proposed by Sakabe et al. [20] and, in order to confirm the validity of this model, the interspaces dependence on laser fluence for Ti, Pt, Mo, W, Si, and SiC have been measured experimentally [21–23]. It was found that the experimental results agree reasonably well with the model. An assumption in the model is that, as a consequence of the ultrafast interaction with the laser beam, the solid surface is initially covered by preformed surface plasma with a density much lower than the solid. Surface plasma waves are then induced at the interface between free space and the laser-produced low density plasma by parametric decay of the incident laser light into a surface plasma wave and a scattered electromagnetic wave. As the plasma wave travels slowly at the interface, an ion-enriched local area appears. Before the next electron wave peak arrives, the ions experience a strong Coulomb repulsive force and can be exploded into vacuum, that is a Coulomb explosion occurs [24–30]. Through this process, periodic grating structures are generated with an interspace corresponding to the surface plasma wave wavelength. Therefore the pre-formed plasma is a key issue to discuss the formation mechanism of grating structures. However, it is technically difficult to measure the composition of the preformed plasma because its

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thickness is too small and its density is also quite low. To confirm the possibility of generation of preformed plasma in such a short time scale, we carried a double pulse experiment on a well-known material, such as Ti, in order to demonstrate that a variation of the surface plasma density might lead to a variation of the periodic grating features.

2. Experimental methods and results

In the experiments, the T^6-laser system (central wavelength $\lambda_L = 805$ nm, pulse width $\tau = 40$ fs, repetition rate 10 Hz) was used for all irradiations. The irradiating beam was composed by two consecutive pulses with a fixed time delay of 160 fs. The first pulse was meant to be responsible for the surface plasma formation and its fluence F_{PP} was varied and always kept below the LIPSS formation threshold fluence F_{LIPSS} on Ti. The delayed pulse was meant to be responsible for the periodic grating structures formation and its fluence F_{LP} was varied and kept always above F_{LIPSS}. The LIPSS formation threshold fluence was experimentally found to be $F_{LIPSS} = 59$ mJ cm^{-2} for 50-single-shots exposure on Ti. From the same measurement it was possible to define the damage threshold F_{TH} of Ti undergoing 50-single-shots exposure, which was about 37 mJ cm^{-2}. The delayed pulse was separated from the main laser beam through a delay line and the two pulses were then collimated and focused to a spot size of about 50 μm on the Ti surface with a lens $f = 10$ cm at normal incidence in air environment. The polarization direction of the first pulse was the same of the delayed pulse. The double pulsed beam was shaped to be spatially flat at the target position by image-relaying only the central part of the original Gaussian profile, which was clipped by an aperture and more precisely trimmed by a second aperture. The target of titanium was mechanically polished. The roughness, Ra, was less than 2 nm for sample. The laser fluence in the flat top region was varied in the ranges of $F_{PP} = 10$–50 mJ cm^{-2} for surface plasma formation. For each value of F_{PP}, three different values of the second pulse fluence were used, that is $F_{LP} = 60$, 100, 150 mJ cm^{-2}. For each couple of values of F_{PP} and F_{LP}, the number of double pulses irradiating the Ti surface was DN = 1, 25. Laser-produced grating structures were examined by scanning electron microscopy (FE-SEM JEOL JSM-7500f).

Fig. 1 shows the morphology of Ti surface produced by double pulse irradiations with DN = 1 (Fig. 1a) and DN = 25 (Fig. 1b). For DN = 1, periodic grating structures are not formed on the surface regardless the values of F_{PP} and F_{LP} used for the irradiations. However, nanoparticles with a diameter ranging from 20 nm to 30 nm were produced on the irradiated area. These nanoparticles arranged to form a periodic pattern with an interspace of about 764 ± 38 nm. Therefore, the nanoparticles formed on the surface after exposure to 1 double pulse might have a key role in the self-organization of the periodic grating structures at higher number of double pulses. The formation of nanoparticle by 1 double-pulse exposure has been reported previously by Kim et al. [31] and a possible model has been proposed to discuss the result obtained after femtosecond laser pulse irradiation at high laser fluences [32]. The mechanism underlying the generation of nanoparticles at such low laser fluence, close to ablation threshold, is still an open question. When nanoparticles are produced on metals irradiated with 1 double fs pulse, the pre-formed plasma might be produced by Coulomb explosion from nanoparticles irradiated by subsequent pulses. The possibility of Coulomb explosion from metal nanoparticles on a metal surface after irradiation with femtosecond pulses, has been previously investigated by time of fight mass spectrometry measurements [25]. The experimental results showed that charged particles are emitted from the nanoparticles after irradiation with femtosecond laser pulses below the ablation threshold fluence. Therefore, the pre-formed plasma can be produced in the rising

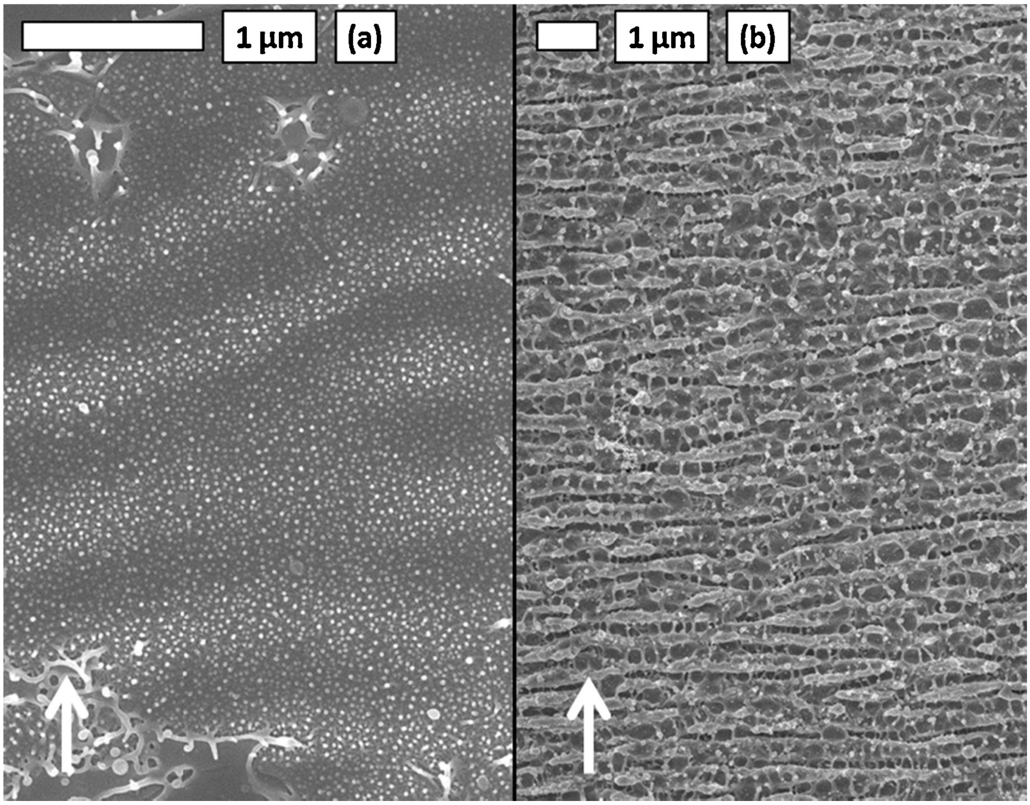

Fig. 1. SEM images of surface structures on Ti produced by 1 double pulse (a) and by 25 double pulses (b) with a time delay between pulses of 160 fs. For both cases, the laser fluence of the first pulse was $F_{PP} = 25$ mJ cm^{-2} and the delayed pulse laser fluence was $F_{LP} = 100$ mJ cm^{-2}.