High-spatial-frequency periodic surface structures on steel substrate induced by subnanosecond laser pulses

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Laser irradiation of solid materials induces many types of morphological, chemical, and structural changes. One of the interesting morphological changes is laser-induced periodic surface structures (LIPSS), in other words, ripples. Spontaneous formation of LIPSS by irradiation with a single laser beam was first reported in 1965.1) The formation of LIPSS was attributed to interference of incident and scattered waves. In this case, the period of the LIPSS, \( \Lambda \), is equal to the wavelength of the incident laser beam, \( \lambda \), at normal incidence. In recent years, however, LIPSS with a period shorter than the laser wavelength (\( \Lambda < \lambda \)) have been formed using femtosecond lasers.3-5) LIPSS with a period significantly shorter than the wavelength (\( \Lambda \leq \lambda/2 \)) are referred to as high-spatial-frequency LIPSS (HSFL) or fine ripples, whereas LIPSS with a period slightly shorter than the wavelength (e.g., \( 0.5 \lambda \leq \Lambda \leq 0.85 \lambda \)) or close to the wavelength (\( \Lambda \approx \lambda \)) are referred to as low-spatial-frequency LIPSS (LSFL) or coarse ripples.

The orientation of LIPSS with respect to the direction of the incident laser beam’s electric field is also of interest. The wavevector of the LIPSS, \( \mathbf{k}_\Lambda \), is usually parallel to the direction of the electric field, \( \mathbf{E} \), but in a few cases, the wavevector is perpendicular to the electric field (\( \mathbf{k}_\Lambda \perp \mathbf{E} \)). For example, HSFL with \( \mathbf{k}_\Lambda \perp \mathbf{E} \) and a period of approximately \( \lambda/4 \) have been observed on diamond films,9) whereas most HSFL on dielectrics have \( \mathbf{k}_\Lambda \parallel \mathbf{E} \). It should be noted that the orientation of LIPSS is often represented by the orientation of each line (ridge/groove); in that case, the terms parallel and perpendicular should be considered reversed in the present article.

It is generally recognized that HSFL are induced only when an ultrafast laser (less than a few picoseconds or a few tenths of a picosecond) is used.4,5) In this article, we report the formation of HSFL by a 0.5 ns laser on a steel substrate. We recently reported the formation of HSFL by a 0.5 ns laser on a prescratched silicon substrate, but the HSFL were formed only along a scratch (as wide as a scratch of few micrometer width).10) This article demonstrates formation of HSFL that are not limited to scratches. In addition, we report the observation of LSFL with orientations that were strongly affected by a pre-existing scratch.

The samples used were steel substrates (SM490, rolled steels for welded structure, defined by [the Japanese Industrial Standards (JIS) J 3106]). The substrates were cut into 10 × 10 mm² pieces, and the surfaces were mechanically polished and then scratched unidirectionally using a P2000 abrasive paper.

The experimental setup for laser irradiation was similar to that in the previous article.10) A linearly polarized subnanosecond Nd:YAG laser (Teem Photonics PNP-M08010) with a wavelength \( \lambda = 1.064 \mu m \) was used as a light source. The pulse energy was controlled using a half-wave plate and a polarizing beam splitter. A lens with a focal length of 100 mm was used to focus the laser pulses. The laser was operated at a repetition rate of 10 Hz. The number of pulses was controlled by a mechanical shutter (Thorlabs SH05/M) that was synchronized to the laser pulse using a single-board computer (Arduino). The morphology of the laser-irradiated substrates was observed by a scanning electron microscope (SEM; JEOL JSM7100F).

Figure 1(a) shows an SEM image of the steel substrate after laser irradiation (70 µJ, 10 pulses). As seen, a concentric...
pattern was observed. This indicates that the formation of different morphologies is determined mainly by the fluence of the laser pulse. Magnified images in the peripheral regions [Figs. 1(b) and 1(c)] show the presence of LIPSS with different orientations and different periods. In the inner part, the LIPSS have an orientation of $k_A \parallel E$ and a period roughly equal to the laser wavelength. In the outer part, the LIPSS have an orientation of $k_A \perp E$ and a much shorter period of about 0.45 µm ($\sim 0.4\lambda$); these LIPSS can be referred to as HSFL. Figure 2 shows another example of the formation of HSFL: SEM images of the steel substrate after laser irradiation with a smaller pulse energy (30 µJ, 10 pulses). As seen in the close-up in Fig. 2(b), the orientation of the LSFL is roughly $k_A \parallel E$, but more precisely, the orientation varies around the kink. The lines of the LSFL are parallel to the scratch, and the LSFL extend more than 10 µm from the scratch. The period of the LSFL is almost equal to $\lambda$; this is different from the LSFL in Figs. 1–3. These results suggest that the formation of LIPSS in Fig. 4(b) is explained by the classical model of interference between incident and scattered waves and that a different mechanism may contribute to the formation of LIPSS with $\Lambda < \lambda$.

Let us discuss the formation of HSFL from the viewpoint of pulse duration. As mentioned earlier, it is generally recognized that HSFL are induced only when an ultrafast laser is used.\textsuperscript{4,5} Before our group’s reports, the longest pulse duration that formed HSFL was 80 ps.\textsuperscript{11} It is well known that in some cases, HSFL do not form even when a femtosecond laser is used, especially on opaque materials.\textsuperscript{12} In contrast, in the present study, HSFL were induced with 0.5 ns laser pulses on an opaque material. In our previous article, we reported that HSFL were formed using the same 0.5 ns laser but were limited to forming only along a scratch. In the present study, the region of HSFL was not limited to the scratch and exhibits two-dimensional expansion. This suggests that we can fabricate HSFL in a much larger area if we scan the sample.

Concerning the orientation, HSFL of both $k_A \parallel E$\textsuperscript{13–20} and $k_A \perp E$\textsuperscript{7,8} have been reported on metals. In these reports, \textsuperscript{112701-2} © 2017 The Japan Society of Applied Physics
there is a relationship between the orientation and the period. For \( \mathbf{k}_\parallel \mathbf{E} \), the period was in the range \( \lambda/3 \leq \lambda/2 \). In contrast, for \( \mathbf{k}_\perp \mathbf{E} \), the period was approximately \( \lambda/10 \). The present result—\( \mathbf{k}_\perp \mathbf{E} \) with a period of about 0.4 \( \lambda \)—does not follow this trend, which was observed with femtosecond lasers. Thus, we can assume that the underlying mechanism in the formation of HSFL is not exactly the same when femtosecond and subnanosecond lasers are used.

In summary, several types of LIPSS were formed on a steel substrate using a 0.5 ns laser at a wavelength of 1.064 µm. In particular, contrary to general understanding, we demonstrated that a subnanosecond laser can induce HSFL. The observed HSFL had periods of \( \sim 0.4 \lambda \), and the orientations of their wavevectors were perpendicular to the electric field of the irradiated laser pulses. This result implies that a subnanosecond laser can be used as an alternative to an ultrafast laser in specific application fields. In addition, we observed that the orientation of LSFL can be strongly affected by a pre-existing scratch on the surface.

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