# Fast Fabrication of Colorful Nanostructures Using Imprinting with Femtosecond Laser Structured Molds

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Femtosecond laser induced periodic surface structures (FLIPSS) on many material surfaces have drawn much attention in recent years. However, the relatively low throughput of direct production process limits its potential of high volume manufacturing (HVM). In this study, fast replication of FLIPSS on Ag parts by imprinting process is demonstrated. An area of the high hardness (HRC 58-60) cold work die steel SKD 11 is irradiated by femtosecond laser pulses with a top-hat beam profile to form periodic-like nanostructures with the periods of 600~700 nm. It was then used for the process of imprinting. An Ag part with nano ripples can be replicated quickly, which proves that HVM of LIPSS on Ag parts is possible.

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## 1. Introduction

Femtosecond laser machining has been recognized as an effective tool for materials surface micro/nano modification. It results less debris contamination, good reproducibility and minimal heat-affected zone. When irradiating a metal surface with femtosecond laser pulses, ripples or quasi-periodic nanostructures or self-organized structures can be formed in a simple one-step process [1, 2]. This technique is referred to as femtosecond laser-induced periodic surface structure (FLIPSS). The formation of periodic nanostructures can be attributed to the interference between incident femtosecond laser wave and the surface scattered wave [3-6] and also the two plasmon decay models [7].

FLIPSS technique has many interesting applications such as fabrication of ultra-low reflectance metal surfaces [8-11], polarization-controlled stainless steel coloration [12], surface wettability tuning of silicon [13-15], glass [16], and metal [17-21]. However, the relatively low throughput of femtosecond laser processing limits the potential of high volume manufacturing. Mass production techniques, such as injection molding, hot embossing, and imprinting process are suitable for plastic or metallic parts.

In this study, fast replication of colorful nanostructures on Ag parts by imprinting using a SKD11 steel die has been demonstrated. The die was first irradiated by top-hat linearly polarized femtosecond laser pulses for nanostructure generation and then used for cold imprinting. An Ag part with surface nanostructures was replicated quickly, which proves that HVM of LIPSS on Ag parts is possible.

## 2. Experimental

The polished SKD 11 steel die was machined using a 120 fs pulse duration regenerative amplified Ti:Sapphire laser system (Spitfire, Spectra-Physics). The central wavelength is 800 nm and the repetition rate is 1 kHz. The linearly polarized laser beam power is continuously adjustable in terms of pulse energy by a automated rotatable half-wave plate and a polarizing beam splitter. The Gaussian laser beam profiled was transformed into a top-hat one by using a beam shaper (piShaper, MolTech). The top-hat beam profile is shown in Fig. 1. The laser beam is focused onto the steel die surface at normal incidence by an objective lens (Mitutoyo 0.26 NA, M Plan Apo NIR). The positioning of the die was done by using a three-axes precision stage. The fabrication process was monitored continuously via a coaxial machine vision system. The surface profile of the LIPSS processed die was observed by using a scanning electron microscopy (SEM).

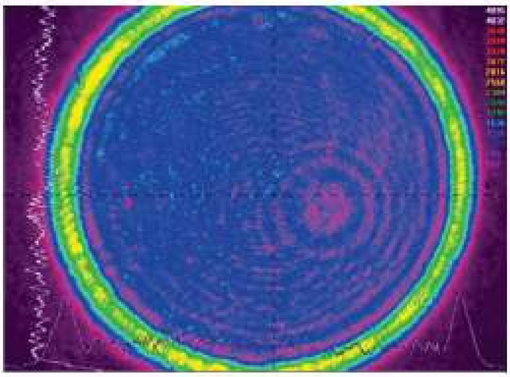

**Fig. 1** The top-hat beam profile.

## 3. Results and Discussion

Fig. 2 presents a SEM image of a single point irradiated by 100 laser pulses at the fluence of 0.48 $J/cm^2$. The profile reflects the irradiation intensity of the top-hat distribution as was shown in Fig. 1. Fig. 3 corresponds to the same laser fluence with different number of laser shots from 10 to 100. It is observed that the appearance of the periodic-like nanostructures is dependent on the number of laser shots received per area. The periodic-like nanostructure evolves with the increasing number of pulses. Previous studies [22] have shown that the processing of diamond-like carbon film using stationary linearly polarized femtosecond laser pulses, the nanostructures also evolves with the increasing number of pulses

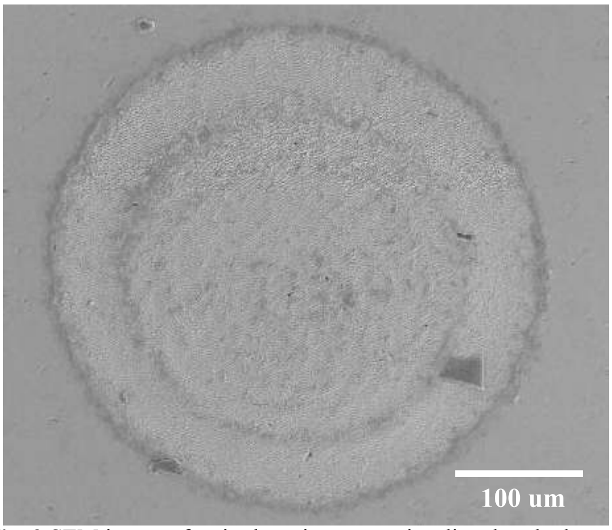


**Fig. 2** SEM image of a single-point pattern irradiated at the laser fluence of 0.48 J/cm$^2$ with 100 shots.

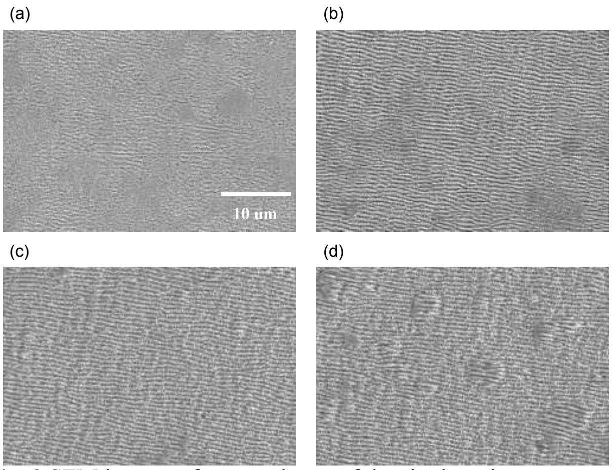


**Fig. 3** SEM images of a central area of the single-point pattern irradiated at the laser fluence of 0.48 J/cm$^2$ with (a) 10, (b) 20, (c) 70, and (d) 100 shots.

Fig. 4(a) presents a low magnification SEM image of the line pattern irradiated at the laser fluence of 0.48 J/cm$^2$ with a scanning speed of 760 mm/min. The scanning direction is perpendicular to the laser polarization. The magnified images of areas A and B are shown in Fig. 4(b) and (c), respectively. As seen from Fig. 4(b), nanostructures with a period of approximately 600~700 nm were formed, which was slightly less than the laser wavelength at 800 nm. In addition, the orientations of the periodic nanostructures were nearly perpendicular to the polarization direction (E). The result agrees with previous studies when linearly polarized femtosecond laser beam was used [4, 5, 23]. In Fig. 4(d), it can be seen that a two-scale morphology consisting of micro- and nanostructures was fabricated [6]. The nanostructures similar to that in Fig. 4(b) are on top of the microstructure. Fig. 5 shows the SEM images of a line pattern written at the laser fluence of 0.48 J/cm$^2$ and scanning speeds of 800, 780, 740, and 700 mm/min. It is observed that the appearance of the periodic nanostructures is independent on the scanning speed, i.e. on the number of irradiation laser pulses received per area.

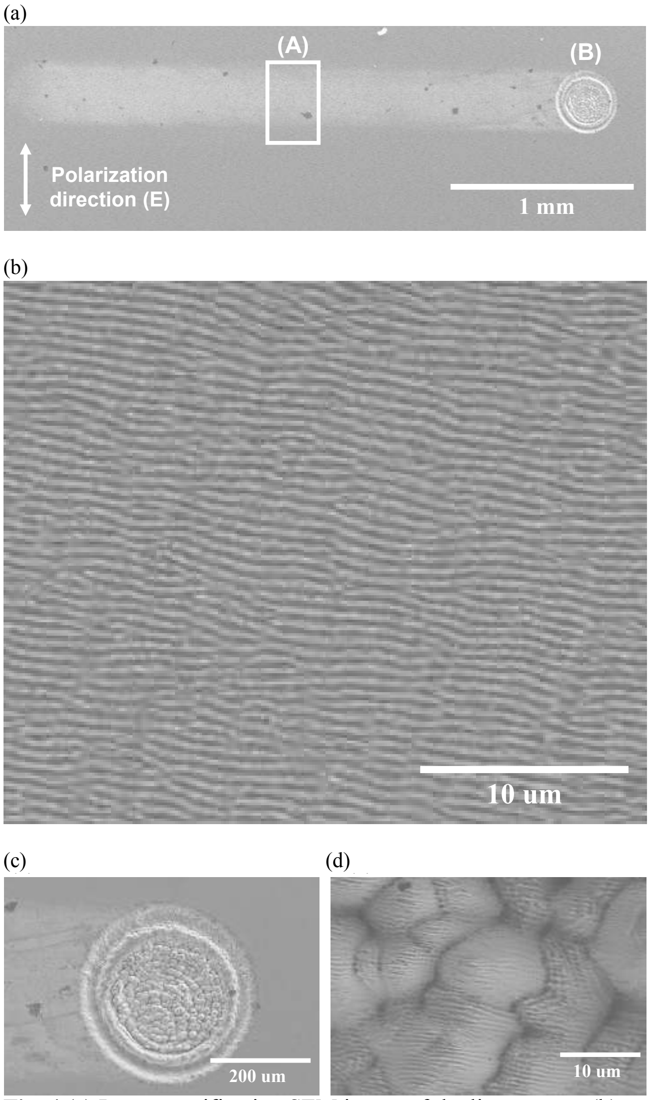


**Fig. 4** (a) Low magnification SEM image of the line pattern, (b) magnified SEM image of the area A, (c) magnified SEM image of the area B, and (d) the central area in Fig. 4 (c).

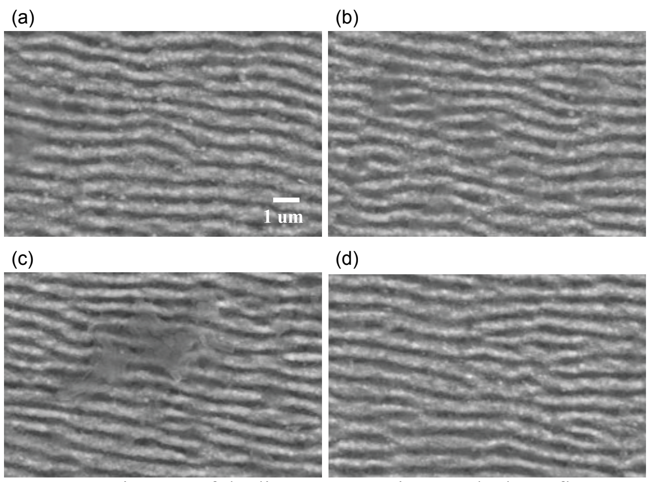


**Fig. 5** SEM images of the line pattern written at the laser fluence of 0.48 J/cm$^2$ and scanning speeds of (a) 800, (b) 780, (c) 740, and (d) 700 mm/min.

Fig. 6(a) shows a photograph of a 20×20 $mm^2$ area on the SKD 11 steel die irradiated at the fluence of 0.48 $J/cm^2$ and the scanning speed of 740 mm/min. Its line pattern is similar to that shown in Fig. 5(c). Fig. 6(b) shows the imprinted Ag part from the die (imprinting pressure 10.58 $N/cm^2$). The colorful reflection can be observed on the laser-irradiated area on both the die and imprinted part. This is due diffraction of illumination white light by the nanostructures. Fig. 6(c) presents SEM image from the square area in Fig. 6(b). The nanostructures were imprinted on the Ag part. The line pattern is not as clear as those shown in Fig. 4(b), which is believed because of the debris of the Ag material got stocked in the die during the imprinting process. However, from Fig. 6(b), the diffraction effect of light is still visible. The imprinted Ag part is metal colorized without its painting. Our finding proves that HVM of LIPSS color metal is viable.

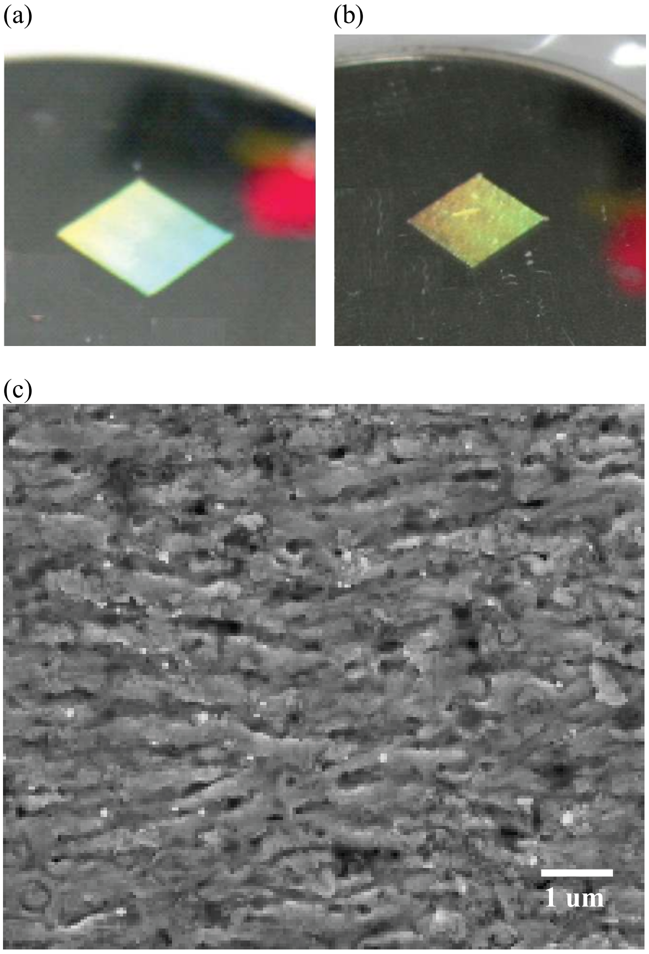


**Fig. 6** Photograph of the femtosecond laser irradiated (a) SKD 11 steel die (b) imprinted Ag part, and (c) SEM image of the square area in Fig. 6 (b)

## 4. Conclusions

This paper has reported a novel low-cost and fast fabrication process for periodic nanostructures using imprinting with a femtosecond laser surface-textured metal die. The SKD 11 steel die was fabricated by the FLIPSS technique using a femtosecond laser with a top-hat beam profile. An array of nanostructures was formed on Ag parts by cold imprinting process. The desired color effect on the imprinted part proves that HVM of FLIPSS color metal without paint is possible.

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