Direct Laser Interference Systems for the Surface Functionalization of Powertrain Components

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Abstract

Periodic patterned surfaces do not only provide unique properties, but act as intelligent surfaces capable of selectively determine various functionalities in applications, such as biomaterials, surface engineering, photonics and sensor systems. In particular, these surfaces have demonstrated control of friction and wear in both lubricated and non-lubricated conditions.

In this paper, we introduce a recently developed approach for the fabrication of two and three dimensional structures using Direct Laser Interference Patterning (DLIP). The fabricated structures range from the sub-micrometer to micrometer scale, and were directly fabricated on metals as well as on diamond like carbon coatings. Different examples of fabricated arrays and their applications in tribology are discussed.

Introduction

Surface patterning does not only provide unique properties, but act as intelligent surfaces capable of selective influencing multiple functionalities of applications in biomaterials [1-4], surface engineering [5, 6], photonics [7, 8] and sensor systems [9]. Numerous techniques have been explored and applied to fabricate such micro- and nano- structures (e.g. nano-imprint lithography, laser writing and optical lithography). However, only a few of them are suitable for the fabrication of periodic structures on different materials in a single process step [10].

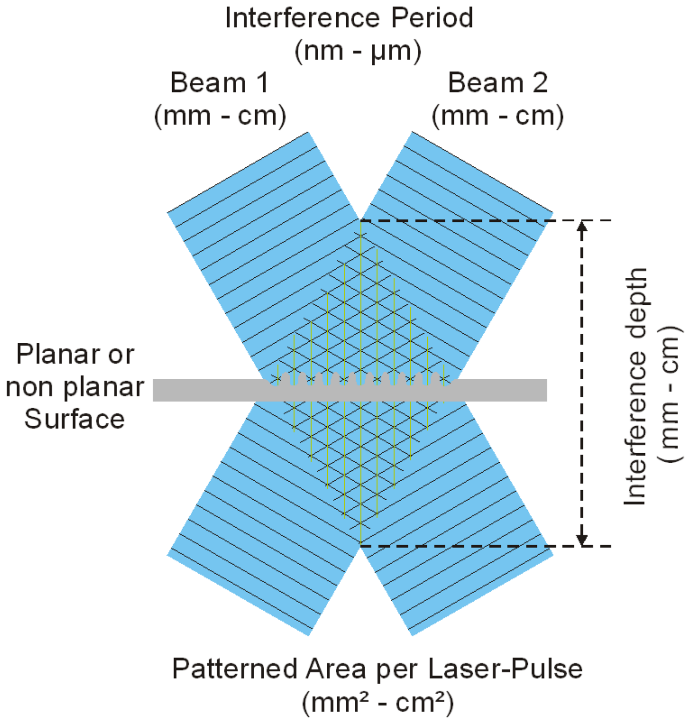

Fig. 1 Schematic of interference principle

One of the more recent advances allowing fabrication of periodic arrays within the micro- and sub-micrometer scale involves Direct Laser Interference Patterning (DLIP) [11, 12]. Interference is the phenomenon observed when two or more waves are in the same space. A method to produce interference patterns consists on splitting a laser beam into two equal intensity beams using a beam splitter. These beams are then reflected by two mirrors and overlapped on the substrate surface. The theoretical principle for a two-beam configuration is shown in Figure 1, schematically. As it can be seen, interference patterns are obtained in the entire volume where the beams are overlapped (Interference Pattern depth in Figure 1). Considering that the beam diameter is larger than several millimeters and that small intercepting angles (2 – 10°) are necessary to obtain a very wide range of patterns, the overlapped volume covers several mm^3. For example, for 10 mm beams with an intercepting angle of 10°, the total overlapping volume over the substrate is ~ 1500 mm^3 (1.5 cm^3). In consequence, the DLIP method is particularly suitable to fabricate periodic patterns on planar as well as non-planar surfaces.

A high power laser with high pulse energy permits it, to directly modify the surfaces of materials in a one step process. Another significant advantage of this technique is compared to other surface patterning methods is that fairly large areas can be processed within a short period of time (up to several cm^2/s) using a single or multiple laser pulses [13]. Therefore, it offers an opportunity of large-scale production.

By selecting the process parameters, this technique is able to create different surface topographies. For example, using a two-beam interference setup, line-like periodic structures can be fabricated (Figure 2a). Alternatively, a three-beam setup allows to fabricate dot-like structures (Figure 2b) while four-beam interference patterning can be used to generate other complex arrays (Figure 2c). In addition to the number of utilized laser beams, also their respective intensity of each individual laser beam produces variation on the interference pattern form, which can be also used to fabricate additional periodic structures. Likewise, different effects such as melting, heating as well as defects and phase transformations can be induced [12]. Therefore, electrical, chemical and/or mechanical surface properties can be periodically and selectively varied.

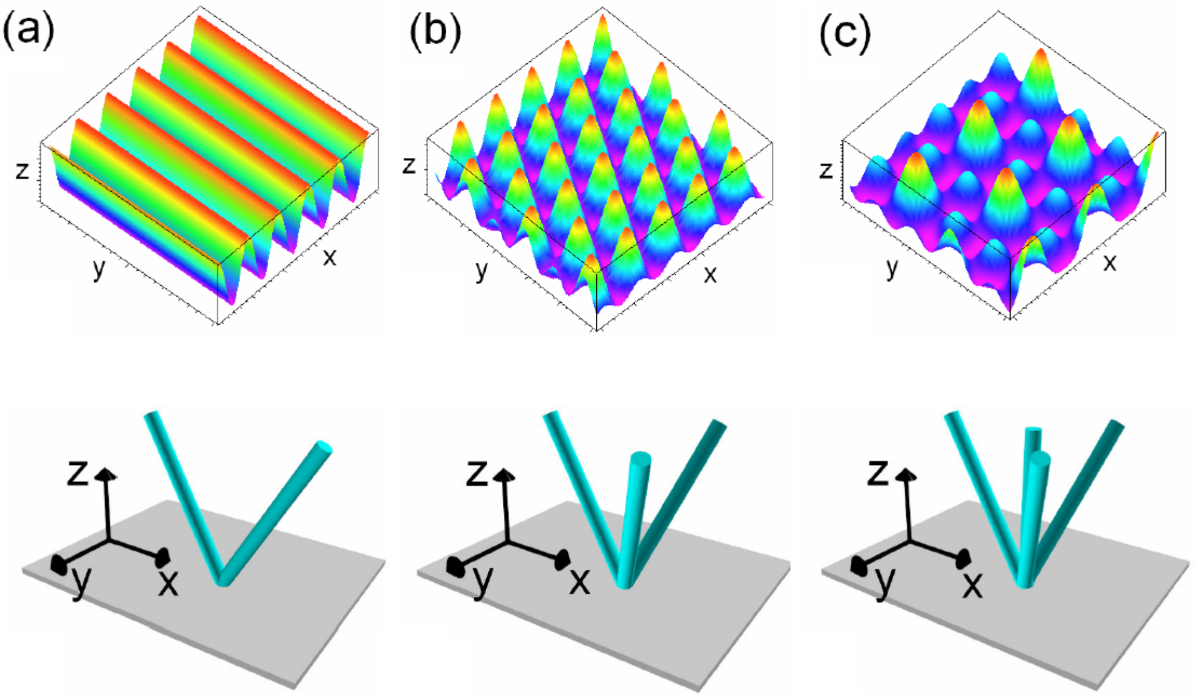

Fig. 2 Simulated intensity distribution of interference patterns using (a) two, (b) three and (c) four laser beams.

Concerning tribology, in the industrialized nations the avoidable losses from friction and wear can add up to 1.5 % of the gross national product, e.g. 35 billion Euro in Germany. With existing technologies and know-how more than 5 billion Euros can be saved.

To improve the tribological performance of components, two basic approaches can be used: (i) surface patterning and (ii) surface coating. Laser surface texturing (LST) is being used in a wide range of tribological applications especially in the automotive industry, by fabricating specific surface structures on mechanical seals, piston rings or thrust bearings among others [14]. Additionally, surface micro texturing has also been used in hard discs and has been considered as an important tool for reducing friction in nano and micro electro mechanical systems (MEMS) [15]. Depending on the application and usage, laser surface texturing can provide several advantages such as minimum contact area and thus adhesive forces, or providing reservoirs for lubricant and wear particles, as well as supporting hydrodynamic effects.

In this article, we discuss the application of the Direct Laser Interference Patterning technology, for the functionalization of powertrain components. At first authors will introduce the main properties of DLIP systems, then highlight examples of tribological applications on diamond like carbon (DLC) and metals (steel) will be described.

Laser Interference Patterning Systems

DLIP has been utilized in the past basically only at the laboratory scale. The method has shown high potential for application in several technological areas. In general, the laser interference experiments are carried out using high power pulsed Nd:YAG laser systems. Typical pulse durations range from 6 to 30 ns. In most of the cases, the infrared wavelength (1064 nm) of Nd:YAG lasers can not be absorbed properly by several materials, the wavelength is normally shortened using non-linear crystals. For instance, through frequency doubling the photons interacting with a nonlinear material are combined to form new photons with twice the energy, and therefore half the wavelength of the initial photons. Similarly, ultra violet (UV) wavelengths (e.g. 355 and 266 nm) can be generated by third (frequency tripling) or fourth (frequency quadrupling) harmonic generation.

Recently, compact interference patterning systems have been developed [16]. These systems offer the possibility not only to process planar surfaces but also complex three dimensional mechanical components including mechanical seals, piston rings, and bearings. Moreover, the system can be adapted in order to precisely fabricate micro or nanometer patterned arrays. The specification data of such a system is given in Table 1. Figure 3, illustrates a DLIP system to produce 1.5 µm line-like periodic arrays for the treatment of 300 x 300 mm^2 substrates. The DLIP optical head is located 50 cm over the working plane and has a size of 15 x 20 x 30 cm^3.

Working distance	5 - 60 cm
Working area	up to 300 x 300 mm^2 (standard dimension, can be also enlarged)
Laser power (wavelength dependent)	up to 25 W (Infra-red)
Pulse energy (wavelength dependent)	up to 2.5 J (Infra-red)
Laser wavelengths	1064, 532, 355 and 266 nm
Repetition rate	10 - 50 Hz
Optical Head dimensions	~ 15 x 20 x 30 cm^3

Structure period	from ~ 180 nm to 20 µm
Fabrication speed	1 - 100 cm^2/s (material dependent)

Table 1: Specification Data of DLIP Systems at Fraunhofer IWS [16].

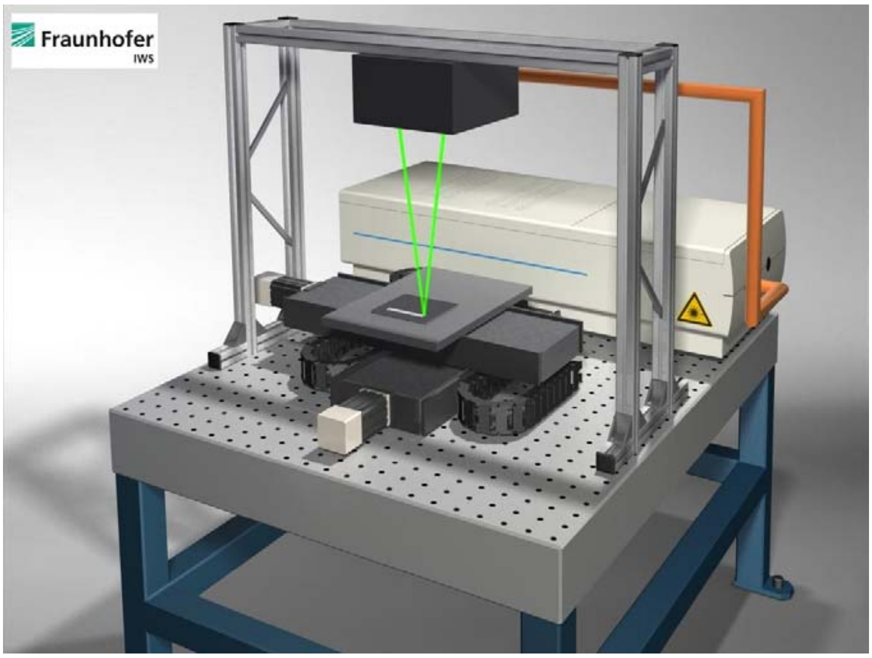

Fig. 3 Schematic of DLIP System (Fraunhofer IWS) [16].

Materials and Methods

Diamond-like Carbon (DLC) coatings were produced using a Laser-Arc-Module. The arc coating systems can be equipped with a magnetic filter to enhance the film quality and reduced the number of particles in the coating. The nanometer thin films in this paper were prepared on polished single crystal silicon substrates. This films have an average roughness < 1 nm. On the other hand, 2.5 µm ta-C films were deposited on polished steel substrates and due to growth defects, the film roughness can exceed a R_a roughness of > 100 nm. This is correlated to an increased wear and friction of the carbon films, due to abrasive effects. A pretreatment of the carbon surface can decrease the abrasive effects. Typical techniques like polishing and brushing can reduce the surface roughness up to values of $R_a \sim 10$ nm and $R_a \sim 30$ nm, respectively. However, depending on the technique employed, different topologies were obtained. In particular, brushing of the deposited DLC films permits it to obtain smoother surface with lower skew as well as smaller kurtosis compared to polishing. Therefore, a better tribological performance is obtained by brushing [17]

Laser interference patterning:

The DLIP experiments were conducted with a Nd:YAG-Laser with 10 ns pulse duration at 266 or 355 nm wavelength (λ). The primary laser beam was split into two beams, which were guided to interfere on the substrate's surface (Figure 1). In this way, a periodic laser intensity distribution is obtained [12]. The spatial period (Λ), representing the distance between two interference maxima, can be adjusted by varying the angle of incidence (α) between both laser beams. For a two-been configuration set-up, the spatial period is described by Equation 1, resulting an intercepting angle of 180° (theoretical geometrical limit), a spatial period equal to half the wavelength ($\Lambda = \lambda/2$) of the incident beam.

$$\Lambda = \lambda / (2 \sin(\alpha/2)) \qquad \text{Eq. (1)}$$

A mechanical shutter was used to ensure that only a predefined number of laser pulses were allowed to hit the substrates. To reduce influences from the optical elements, high flatness of the splitters and mirrors are needed to construct the optical system.

Tribological characterization:
The tribological performance of the films was determined with a reciprocating ball on disc method (CSM) under ambient conditions. A ball of 100Cr6 with a diameter of 6 mm, coated with 1 µm ta-C was utilized. The maximum linear speed was 3 cm/s, normal load 1 N and the sliding distance 1000 m, corresponding to 1/2 amplitude per cycle of 0.5 mm and 10^6 cycles. Prior to the experiment the test specimens were cleaned with isopropanol in an ultrasonic bath and dried at ambient temperature. After cleaning the substrates, an oil based lubricant (10W60) was deposited on the substrates using spin coating method.

Surface characterization:
A scanning electron microscope (SEM, operating voltage: 5 kV) and an atomic force microscope (AFM, operating: contact mode) were used to characterize the surface topography of the irradiated substrates.

Tribological performance of structured DLC coatings

Diamond like carbon films present attractive properties such as high hardness, low friction and wear, as well as excellent biocompatibility. Moreover, tribological DLC coatings are increasingly being applied in the automotive industry, with typical applications in fuel injection system and piston bolts [18, 19].
DLC coatings are characterized by a high content of sp^3 bonded carbon atoms. Within the family of DLC coatings, tetrahedral amorphous Carbon (ta-C) has the lowest friction (superlubricity) and the highest hardness (between 4000 and 6000 HV). Moreover, ta-C coatings present one of the lowest coefficients of friction (COF) under non-lubricated conditions, which is especially important for applications where insufficient lubrication occurs. As an example, using ta-C coatings, the coefficients of friction in the camshaft-bucket tappet could be reduced by 45% [20]. On the other hand, hydrogen containing carbon coatings (a-C:H) are limited to lower hardnesses (2000-3000 HV) and a higher friction under ambient conditions. In consequence, tetrahedral amorphous carbon was selected for our tests.

In order to fabricate a textured surface pattern, at first the proper conditions for the structuring of the ta-C films were investigated. Due to high absorption of the films, especially in the UV-range, as well as their low thermal conductivity, these materials present ideal properties to be structured using laser radiation. Moreover, depending on laser processing parameters and layer thickness, different effects can be observed. At lower laser intensities, the layers are graphitized which means an increase of the sp^2 content [21]. At higher laser intensities, it produces delamination of the layer together with the formation of graphitic clusters in addition to a crystalline structure. However, by using a periodic variation of laser intensity, like in an interference pattern, these effects can be induced locally at the positions, corresponding to the interference maxima.
For example, in Figure 4a, graphitization, delamination and ablation of ta-C thin films with 60% sp^3 content are shown. The spatial period (Λ) was in this case 5.0 µm. Another example is depicted in Figure 4b, where 180 nm arrays were fabricated using 266 nm of laser wavelength. Also in this case,

the material corresponds to ta-C films with 60% of sp^3 content. Due to the low laser energy density employed, the film was locally graphitized at the interference intensity maxima positions, while at the minima the material remained unchanged.

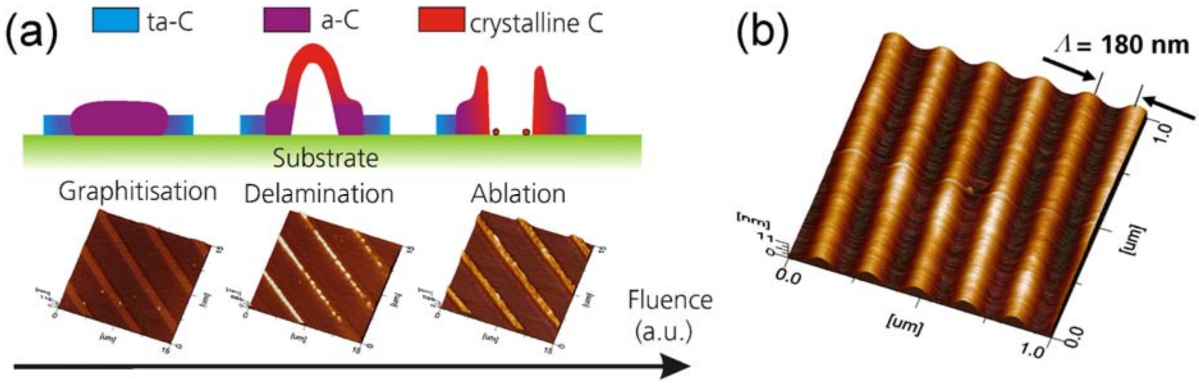

Fig. 4 (a) Schematic representation and experimental results of DLIP induced graphitization, delamination and ablation of ta-C. The DLIP experiments (spatial period = 5 µm) were performed at 48 nm thick ta-C with laser fluences of 38, 75 and 90 mJ/cm^2, respectively (at266 nm of laser wavelength). (b) Patterned ta-C layer with spatial period (Λ) of 180 nm.

As an application example, the tribological properties of structured and non-structured ta-C films were determined. Tribological test on brushed (2.5 µm) ta-c coatings were performed in linear-reciprocating mode with a linear speed of 3 cm/s. A friction coefficient (µ) of ~ 0.08 was measured applying a normal force of 1 N and using a ta-c coated (1 µm) 100Cr6 ball with a diameter of 6 mm. On the other hand, structured ta-C films with a cross-like topography and a spatial period of 10 µm (fabricated using 10 laser pulses and a laser fluence of 450 mJ/cm^2, see Figure 5a) presented a friction coefficient of approximately 0.06, which represents a reduction of 25% (Figure 5b). This excellent tribological characteristic provides the opportunity to replace lubricated systems by unlubricated ta-C coated systems.

In another set of experiments, the friction coefficient of structured and non-structured ta-C films was also measured under lubricated conditions (Oil 10W60) and compared to the tribological performance of steel, as depicted in Figure 6. The measured COF of steel vs. steel was about ~ 0.13, value that has been also measured by other authors [19, 20]. By coating the test specimen with a 2.5 µm ta-C layer, the coefficient of friction was reduced up to ~ 0.04. By adopting a second 1 µm ta-C layer (not polished or brushed) over the 100Cr6 ball, the COF was further reduced to ~ 0.03. A further decrease of the COF was achieved by patterning the ta-C coating of the test specimen with a crossed-like pattern of 10 µm period. In the later case, the friction was reduced to ~0.02. Therefore, compared to untreated steel surfaces, the friction coefficient for a patterned ta-C layer against ta-C was reduced up to 83% (absolute). Moreover, structured ta-C shows an additional improvement of 25 % compared to unpatterned ta-C films. In all cases, any evidence of wear on the ta-C coated specimens was observed.

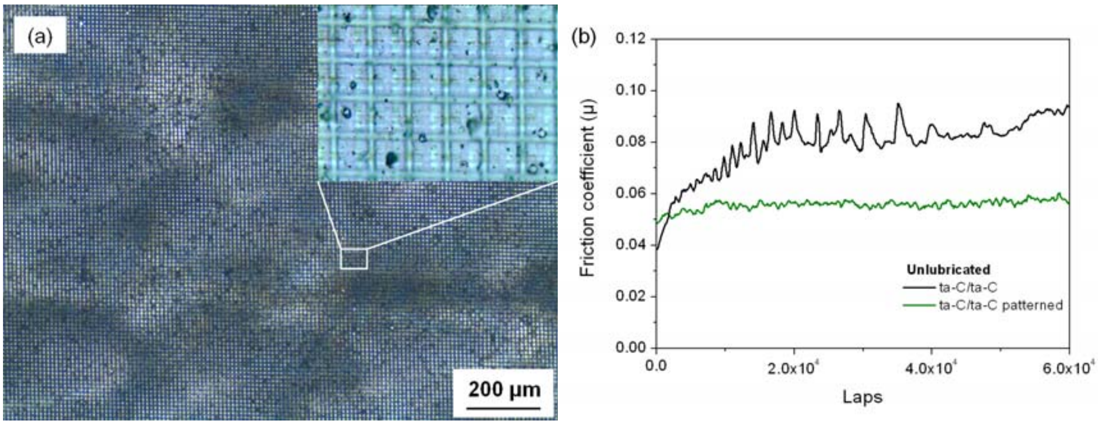

Fig. 5 (a) Cross-like pattern on ta-C with 10 µm period. (b) Friction coefficient of ta-C/ta-C and ta-C/ta-C patterned without lubricant measured over 10^5 cycles

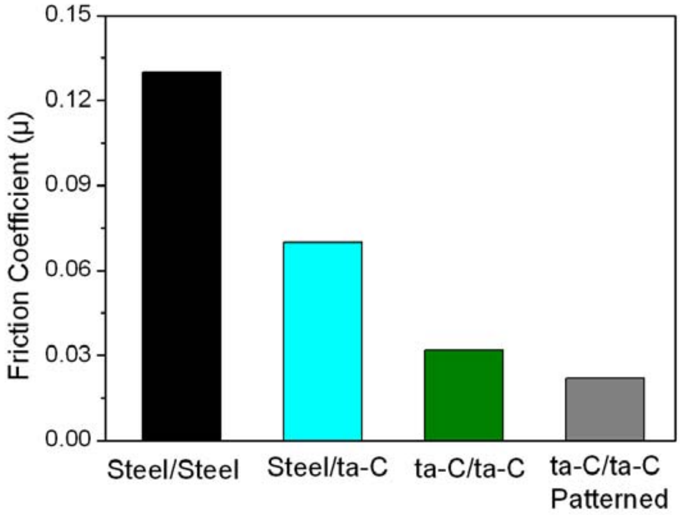

Fig. 6 Friction coefficient of steel/steel, steel/ ta-C, ta-C/ta-C, ta-C/ta-C patterned (lubricated conditions).

Tribological performance of structured metallic samples

Surface patterning of metallic surfaces can be also used to modulate tribological properties under lubricated and unlubricated conditions. Using two and three beam configurations, line-, cross- and dot-like structures were fabricated on steel (Figure 7). The patterning process in this case involves a photo-thermal induced local melting and/or ablation at the interference maxima positions. Moreover, from the SEM-micrographs of Figure 7, the distribution of the molten material after the solidification can be observed.

According, to previous investigations, depending on the pulse duration of the laser system, the laser energy density (laser fluence), the thermal properties of the irradiated materials as well as the spatial period of the interference patterns, different temperature differences between the intensity maxima and minima positions (thermal gradient) can be induced [22, 23]. For example, for 5 µm periods, temperature differences over 2000 – 3000 K are usual, that means that the metal can be locally molten at the interference maxima positions. According to the Marangoni convection, an important temperature difference (in our case between the interference maxima and minima) can induce a flow of the molten material towards the cold regions. In consequence, the molten material at the interference minima is directed away and towards the minima positions. This convection is driven by the surface tension gradient, which is induced by the temperature gradient as explained before. However, this effect dominates the formation of the periodic structures only if the temperature gradient is sufficiently high and the material is predominantly molten at the interference maxima. If the vaporization temperature is reached, the recoil pressure of the ablated material becomes the dominant effect and thus a turbulent flow occurs in the molten metal (high Marangoni number). Regular shaped and smooth patterns are formed if the ablation is minimal, and the material is molten at the interference maxima (in the case of metals). Therefore, the quality of the pattern strongly is influenced by the laser processing parameters.

Experimental observations in stainless steel substrates have shown that the laser fluence, which causes decreased on the pattern quality ranges from 1 to 1.5 J/cm^2, depending on steel type. This data fits very well with theoretically calculated energy density necessary to induce vaporization of steel surface (~ 0.9 J/cm^2) at the interference maxima position. Additionally, the thermal diffusion length of stainless steel is 1.3 µm (for a laser pulse duration of 10 ns). This value fits very well to the smallest possible surface structures (1 µm) that can be fabricated on these materials. In consequence, the smallest possible periodic structure that can be fabricated on a metallic substrate is related with the thermal diffusion length, since smaller spatial periods of an interference patterns do not allow to obtain a considerable temperature difference between maxima and minima positions.

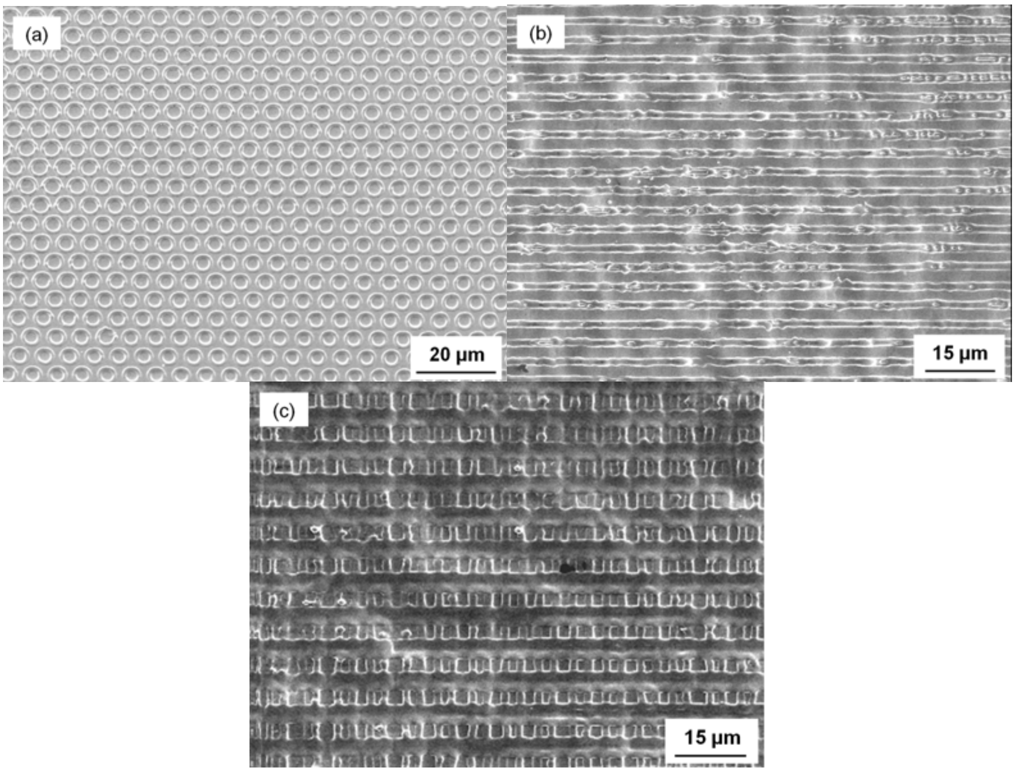

Fig. 7 DLIP patterning of steel a) one dimensional dot-like patterning with a period of 5µm, b) Line-like Patterning with a period of 5 µm and c) Crossed-like pattern with 10 µm.

The requirements for surface patterns for tribological applications are a smooth shaped surface to avoid abrasive wear and minimize adhesive friction. Thus the patterning parameters especially for metals have a high relevance for their tribological performance. In Figure 8, the coefficient of friction of cross-like patterned steel samples is shown. The patterning period in these examples is varied between 5 µm and 15 µm, respectively. The results indicate an improvement of 23 and 33 % for the cross-like structures with 5 and 15 µm, respectively. However, not only the spatial period is relevant for the improvement of the tribological performance, but also the structure shape as well as the ratio between the structure depth and the spatial period, generally described as the aspect ratio.
Previous tests have also demonstrated that such periodic surface patterns in the micron-scale range (2 – 10 µm) can be used to increase the lubricant lifetime by a factor of 16 [14]. This effect is highly relevant in the case that insufficient lubrication at specific positions of a three dimensional part take place, since adhesive forces can result in frictional welding like in steel components (i.e. piston seizures).

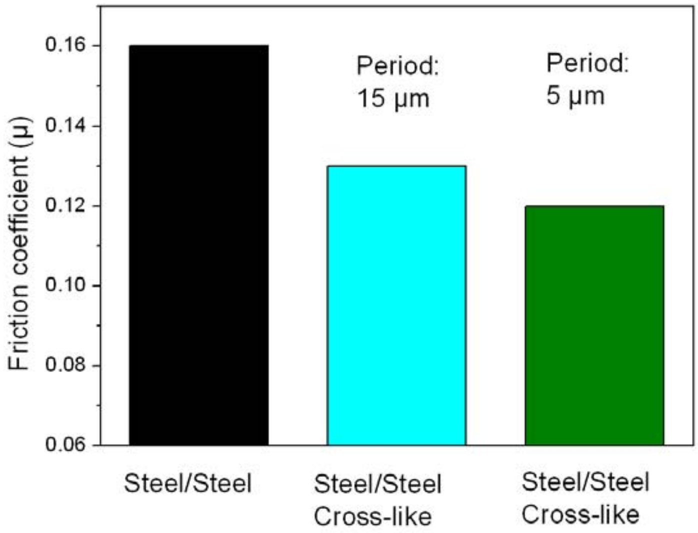

Fig. 8 Friction coefficient of steel/steel, steel/ ta-C, ta-C/ta-C, ta-C/ta-C patterned (lubricated conditions).

Conclusions

We have introduced a new development method to produce surface textures on large areas, to improve the tribological performance of powertrain components. A general knock-out criteria for laser patterning are the patterning speed as well as the size of the required surface structures. However, in the case of direct laser interference patterning (DLIP), both criteria can be fulfilled since even sub-micrometer are achieved at patterning speeds of several cm² per second.

The surface structures produced on metal as well as on DLC coatings can be used to improve the tribological performance of surfaces under lubricated and unlubricated conditions. From one side, the application of carbon coatings enables to operate mechanical systems without lubricant. Moreover, the fabricated structures present long durability since no wear tracks could be observed over the carbon coatings after 10^5 cycles. Under lubricated conditions, both patterned ta-C coatings and steel materials permitted to decrease the coefficient of friction with values ranging from 20 to 33 % for a large variety of surface structures. In consequence, these textured surfaces can be used to improve tribological behavior of the target material especially under lubricant starved conditions.

Acknowledgments

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