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Surface functionalization of forming using direct laser interference patterning for dry forming applications

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Abstract

Forming processes typically require the use of lubricants to reduce friction and wear of the tools as well as to protect the semi-finished products. Since cleaning of forming products is costly and time-expensive, there is a need to eliminate the use of lubricants. An approach to improve the performance of tools in dry forming is by producing micro structured tools or even to structure the semi-finished products. This study presents an overview about the potential application of direct laser interference patterning for the functionalization of surfaces involved in dry metal forming processes.

Keywords: Dry forming, micro structuring, ta-C coating, direct laser interference patterning

1 Introduction

Forming processes in general and deep drawing processes in particular necessitates the use of additional lubricants to reduce the interfacial forces between tool and work piece. In presence of a lubricant, friction and wear is significantly reduced which in turn avoid cold welding of paired surface and ultimately increase tool lifetime and enhances surface finishing of products. Hence, lubricants allow for an efficient operation in metal forming and for a reduction in energy consumption. However, lubricants typically remain on the tool and work piece after forming and necessitate additional surface cleaning steps - a serious environmental and economic issue [1]. Even concepts employing a strongly reduced amount of lubricating species showed no solution to the general problems provoked by the use of lubricants [2].

In consequence, there is a need for concepts based on a complete lubricant free forming process – namely dry forming. A possible approach to a lubricant-free forming process can be the use of functional coatings, which have the task to replace the lubricant and take over its functionality. This includes basically the separation of the contacted surfaces to avoid property transfer, the reduction of friction and wear caused by direct surface interactions such as cold welding as well as the associated heat dissipation in the tribological system [3, 4].

Various research activities focused on the use of protective coatings on tool pieces in order to realize lubricant free forming process [5-9]. Unfortunately, many studies are based on laboratory conditions and up to now, it was not possible to realize a total lubricant-free forming process [10]. A highly promising approach to circumvent the complex cleaning steps of tool and work piece can be the coating of tools by tetrahedral amorphous carbon (ta-C) films [11]. Ta-C films are well known for their impressive tribological characteristics in reducing friction and wear in many applications and environments and the bare use of ta-C coatings can lead to comparable in dry forming processes compared to experiments under lubricated conditions [12].

Recent studies show that the tribological performance of ta-C coatings can be further improved by a texturing of the surface [13-16]. Consequently, this work focuses on structuring concepts and applications of both, the ta-C coated tools as well as the semi-finish materials in order to realize new surface functionalization for use in dry forming processes.

In this study, determination of the graphitization thresholds which are necessary in order to define the process window (from IR to UV) for a defined sp^3 to sp^2 phase transformation are performed. Thereafter, a ta-C coated tool for draw-bend tests is structured by DLIP [17]. Since the coated tool geometry is typically non-planar, deviations of the structure period as function of

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the inclination angle are investigated. Finally, structuring results of the work steel DC04 are presented which potentially offer the possibility for the optimization of the dry forming process.

2 Experimetal

2.1 Materials

The ta-C coatings were applied on flat-steel as well as draw-bend tool surfaces of 1.2379 work steel by a PVD coating plant MZR 373 by Metaplas Oerlikon. More details about the design and mode of operation can be found elsewhere [18, 19]. The resulting hydrogen-free ta-C films had a thickness of about 4 µm and a sp^3 content of roughly 51 %.

2.2 Direct laser interference patterning

The DLIP experiments were performed using ns-pulsed (IR, Green, UV) solid state laser systems. The line-like patterns on the surface were generated as follows. The laser beam is separated into two sub-beams by a beam splitter configuration. These sub-beams are overlapped on the sample surface at a specific overlapping angle β (see Fig. 1) which together with the laser wavelength determines the spatial period of the interference pattern. More details about the experimental setup are presented elsewhere [14]. All experiments were performed with a single laser pulse and under ambient conditions.

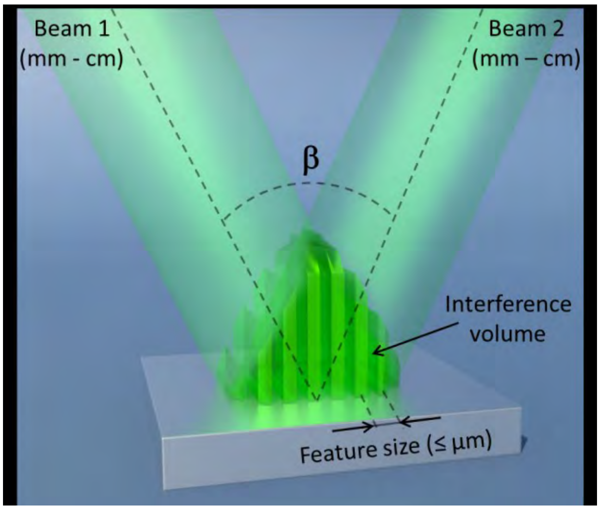

Fig. 1: Schematic representation of the direct laser interference patterning technology for the structuring of materials. Here, a two-beam configuration is shown, which results in the formation of a line-like laser intensity pattern.

3 Results and Discussion

3.1 Graphitization threshold of ta-C

The local transformation of the ta-C coating by laser irradiation from sp^3-hybridized carbon into sp^2-rich material was thoroughly investigated on the flat-steel sample. It was found that the $sp^3 \rightarrow sp^2$ transformation for the given sp^3/sp^2 ratio within the ta-C coating is strongly dependent on the employed laser wavelength. By using the scheme of Mannion et al. [20], sp^3 to sp^2 conversion thresholds of 204 mJ cm^{-2} and 595 mJ cm^{-2} were found for laser wavelengths of 263 nm (UV) and 1053 nm (IR), respectively. These results show that the processing of ta-C films by UV laser radiation requires less laser energy density what is in good accordance with literature [21].

Further experiments focused on the structuring mechanism of the ta-C coatings when using DLIP. Fig. 2a shows a ta-C coated flat surface which was structured by DLIP with a structure period of Λ = 2.3 µm (263 nm laser wavelength). Due to the Gaussian intensity distribution of the laser beam, a gradual change in the interference pattern can be observed on the ta-C surface.

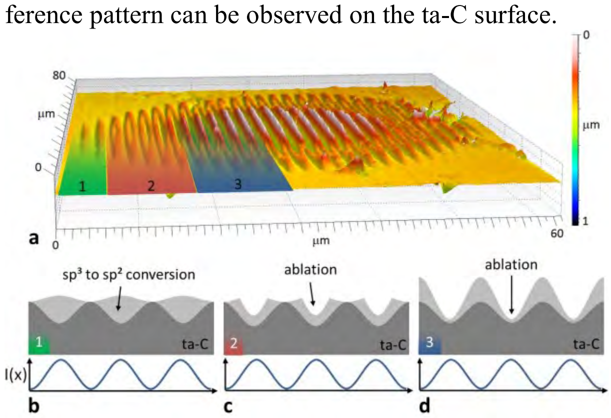

Fig. 2: (a) Example of DLIP patterned ta-C surface. Schematically presentation of (b) locally transformed ta-C surface due to laser irradiation, (c) initial ablation of sp^2-rich areas and (d) complete ablation of sp^2-rich areas. The function I(x) represents the spatial laser intensity.

The region 1 in Fig. 2a shows that for small laser fluences, the sp^3 to sp^2 conversion threshold of ta-C is exceeded at the positions of the interference maxima. As a result, a local sp^3 to sp^2 transformation takes place (see Fig. 2b). This leads to a local decrease in atomic density associated with a localized surface swelling of the ta-C layer. A further increase in laser fluence exceeds the ta-C ablation threshold and leads to a gradually increasing ablation of the sp^2-containing areas at the interference maxima (see Fig. 2c). Concomitantly, surface swellings also start to occur at the positions of the interference minima due to thermal diffusion of heat from the interference maxima. This effect is highly pronounced for structure periods Λ smaller than 5 µm [16]. The region 3 in Fig. 2a indicates the surface region where the sp^2-rich material at the interference maxima is strongly ablated with a further accumulation of heat at the minima resulting on larger amounts of graphitized material (see Fig. 2d).

For the structuring of the coated draw-bend tools, laser fluences below the ablation threshold (according to Fig. 2b) were used.

3.2 Structuring of draw-bend tools

During the deep drawing process, significant friction forces can be observed in the region of the drawing ring radius due to the wrapping of the work piece. Consequently, the drawing ring radius offers a huge potential for minimization of friction forces especially under lubricant-free conditions. Typically, draw-bend tests are employed to study the tribological behavior at the drawing ring radius [10]. Fig. 3a exemplifies the non-planar contact area of the draw bend tool, which was structured by the DLIP process with 532 nm ns-pulsed laser system. Fig. 3b shows a microscopic image of the draw-bend tool surface which was structured with a structure period of Λ = 10 µm. Despite the non-planar geometry of the tool surface, the DLIP structures are well defined all over the tool surface.

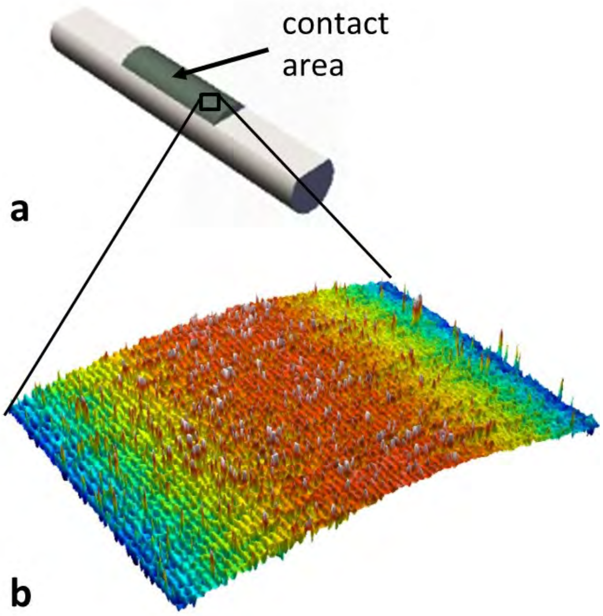

Fig. 3: (a) Coated draw-bend tool which was structured by DLIP. (b) Microscopic image of the DLIP structured contact area on the coated draw-bend tool which exhibit a structure period of Λ = 10 µm.

However, local deviations of the structure period were observed. These deviations result from the curved geometry of the processed sample [22]. Consequently, additional investigations focused on the influence of the tool geometry on the structure periodic of the patterns fabricated using DLIP. Here, it was of fundamental interest to investigate how strongly the non-planar surface geometry influences both the local structure period and the structured area per laser pulse. While the former directly influences the structure geometry, the latter is highly important to determine how fast a forming tool can be processed. Note that the area of interfering laser beams is typically smaller (from µm to cm) compared to the total treated area. Consequently, the sample surface has to be moved relative to the interference setup to achieve a homogeneously textured surface, as shown in Fig. 4a.

The deviation of the structured area per laser pulse in dependence on the angle of inclination γ of the sample surface is depicted in Fig. 4b in terms of length and width of the structured area. As can be seen, an acceptable interference area on the sample surface can be achieved in region 1 (γ<12.5°). In this area, also the target structure period can be considered as constant (results not shown). Higher angles γ show strong deviations in terms of structure quality, as can be seen in region 2 of Fig. 4b.

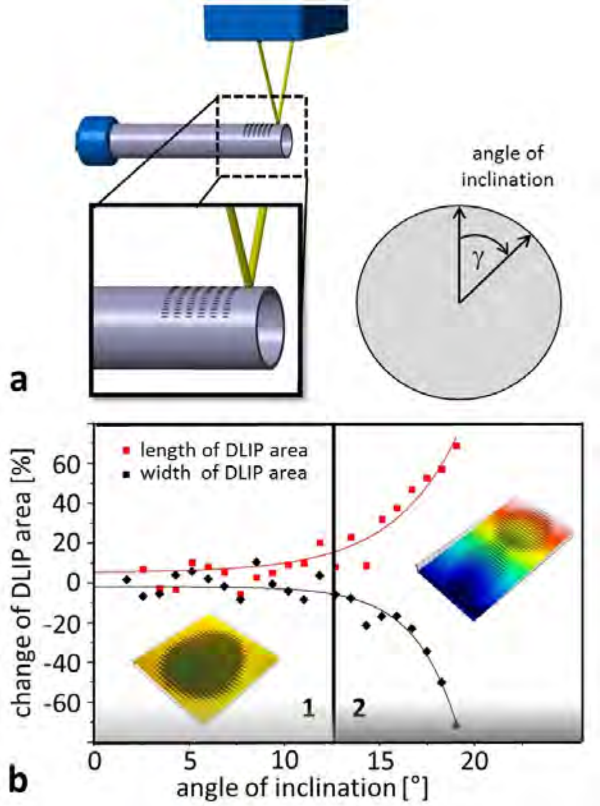

Fig. 4: (a) Experimental DLIP Setup for the structuring of non-planar surfaces. (b) Observed deviations of the structured area in terms of length and height per DLIP laser pulse. Area 1 (γ < 12.5°) depicts the acceptable interference area on the clamping surface whereas area 2 (γ > 12.5°) shows strongly increasing deviations in structuring quality.

3.3 Structuring of semi-finished DC04

While the structuring of the tool surfaces is highly attractive from a tribology and lifetime point of view, the structuring of the semi-finish material is typically not attractive due to its large area. While this is true for nearly all structuring methods, DLIP offers the industrial scalability to achieve structuring speeds of about 0.36 m^2/min directly on metal surfaces [23]. Such high structuring speeds can be performed by using high power laser systems (e.g. 200W at 1064nm wavelength).

Consequently, the DLIP technology offers a real possibility to functionalize the semi-finish DC04 parts. The main objective of the laser treatment is to reduce the effective contact area between the tool and work piece or to control the material flow during a deep drawing application. Fig. 5a summarizes the achievable structure depths on the steel material DC04 as function of the structure periods (Λ = 2, 5 and 10 µm) and the utilized laser fluences.

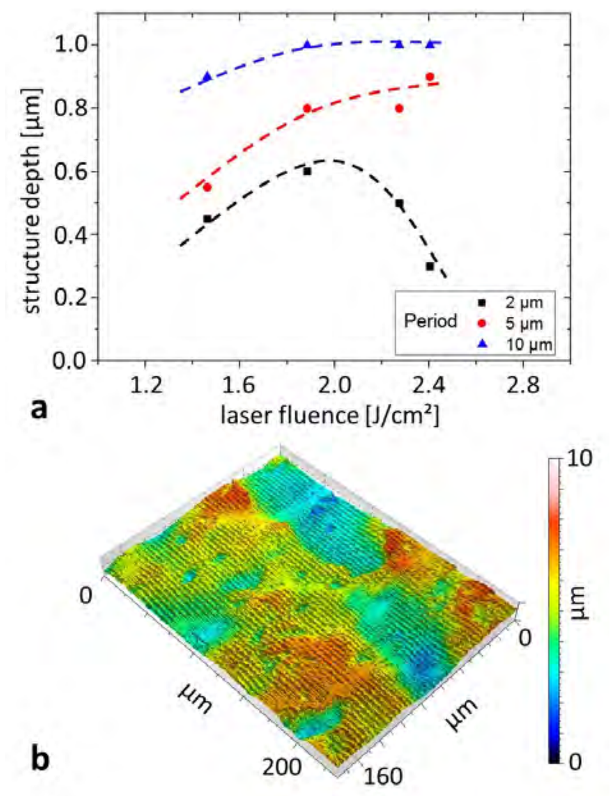

Fig. 5: (a) Structure depth as function of the employed laser fluence for Λ = 2, 5 and 10 µm structure periods (DC04 steel). (b) Surface topology of a DC04 steel surface after DLIP processing with a structure period of Λ = 5 µm (laser fluence: 2.3 J/cm²).

The results show that the largest structure depths can be achieved for the largest structure periods. However, the highest aspect ratio (AR), defined as the quotient between the structure depth and the spatial period, is achieved for the smaller periods (e.g. AR = 0.3 for Λ = 2 µm; AR = 0.1 for Λ = 10 µm). Note that the structure depth stagnate for laser fluences higher than ~2 J/cm² in the case of Λ = 2 µm. This can be attributed to the excessive melt of the surface, especially for smaller periods due to Marangoni convection. The typical quality of a produced pattern on a DC04 surface is shown in Fig. 5b. In this case, the spatial period was Λ = 5 µm. The image shows that the line-like periodic structure is well defined all over the steel surface regardless of its initially relatively high surface roughness of about Sz=10 µm. On the other hand, the processability of non-polished surfaces could be demonstrated, what is necessary for the treatment of real parts.

4 Summary

In this work, both the structuring of ta-C coated draw-bend tools as well as semi-finish DC04 steel was demonstrated. Graphitization thresholds according to the scheme of Mannion *et al.* were determined for IR and UV laser radiation which define the process window for the laser structuring process. A sp^3 to sp^2 graphitization threshold of 204 mJ/cm² and 595 mJ/cm² was found for a laser wavelength of 263 nm (UV) and 1053 nm (IR), respectively. In the case of the DLIP process, three different structuring conditions have been identified. The structuring topography changes depending on the applied laser fluence where low fluences show a gradual sp^3→sp^2 conversion of ta-C material without material ablation while higher fluences lead to pronounced ablation phenomena. A detailed study about the ablation mechanism on ta-C coatings will be published elsewhere [18].

The structuring of the ta-C coated draw-bend tools showed that the structure quality is most pronounced for inclination angles of γ<12.5°. The structuring of the semi-finished material DC04 showed that higher aspect ratios can be reached for lower structure periods. It was also demonstrated that DLIP structuring can be performed despite non-planar tool geometries as well as high surface roughness.

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