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Laser embossing of micro- and submicrometer surface structures in copper

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Abstract

Micro- and submicrometer structures have been transferred from nickel foils into solid copper surfaces by laser microembossing. The developed arrangement for laser microembossing allows a large-area replication using multi-pulse laser scanning scheme, guaranties a low contamination of the embossed surface and enables the utilization of thick workpieces. In the micrometer range the replicated patterns feature a high accuracy regarding the shape. A significant difference between the master and the replication pattern could be observed for the laser embossing of submicrometer patterns. In conclusion, the results show that the proposed laser embossing process is a promising method with a number of applications in microengineering.

Keywords: Laser; embossing; replication; metal; micro; submicro patterns; copper

1. Introduction

The patterning of metal surfaces with three-dimensional (3D) structures is of rapid growing interest because of the ongoing miniaturization and the increasing complexity of microelectromechanical systems (MEMS). Current techniques which are used for 3D micromachining of MEMS structures like photolithography and wet chemical or deep reactive ion etching cannot be easily transferred to metals due to the different etching chemistry. Further, these techniques require complex fabrication processes but allow only the generation of a limited variety of different surface structures. Metal patterns can be fabricated by, e.g., electrochemical machining or electroplating but some restrictions regarding the pattern size and the used metals are known [1].

Replication and embossing technologies are often utilized for 3D patterning of polymers to enable a low-cost and high-throughput fabrication. However, these techniques mostly base upon the ability of

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material softening at low temperatures or the possibility of curing monomers to polymers; therefore these techniques are mostly not adaptable for other solid metals.

The fabrication of submicrometer and nanostructures by laser-assisted direct imprinting (LADI) was demonstrated recently [2]. However, a transparent mould and melting of the metal layer by laser pulses is necessary for replication. Laser microembossing is another possibility to be utilized for the fabrication of three-dimensional metallic structures. This approach, however, basically is a mechanical driven, non-thermal laser fabrication process. The energy which is required for the embossing process is induced by high pressure caused by the ablation of an auxiliary material or coating which covers the workpiece. Up to now, only a few studies were published which deal with laser microembossing of 3D metallic structures at thin metal sheets [3, 4]. In the papers of Cheng et al. the grain size reduction of thin metallic foils, the forming behaviour, and limitations due to the laser forming process were investigated [5-8]. Liu et al. investigate the application of micromould-based laser shock forming for MEMS applications [9, 10], Vollertsen et al. investigate laser deep drawing of different thin metallic films and the forming limit of metallic foils at micro deep drawing [11, 12].

The aim of the present paper is to study an improved methodology of laser microembossing that enables also the surface patterning of solid workpieces. The presented laser microembossing methodology bases on laser scanning instead of the commonly used single-pulse irradiation and enables the replication of fields larger the spot size. To show the potential of this approach the size of the generated structures was reduced from tens of micrometers into the submicrometer range. The generated structures were examined by scanning electron microscopy (SEM), atomic force microscopy (AFM), and white light interference microscopy (WLI) in order to investigate the characteristics of the laser embossing process.

2. Experimental

In the present study solid copper pieces with a diameter of ~ 2 cm and a thickness in the range of 1 to 2 mm were used as workpiece. The samples were prepared by sawing, soft annealing, and subsequent polishing of the surface. Two different nickel foils with a thickness of about 3 µm were used as master forms. Because of the higher hardness of the nickel foils in comparison to the copper it is believed that the plastic deformation of the copper surface occurs at a much less mechanical energy than it is needed for the deformation of the nickel foil and because of this the nickel foils are not or only slightly affected due to the laser embossing process.

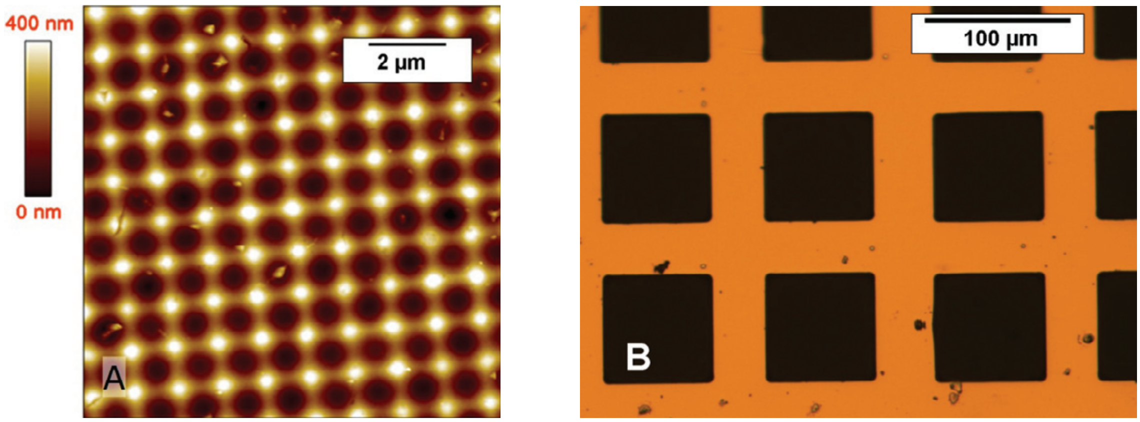

Fig. 1. (Left) AFM images of the nickel foil used as master form (A), (right) optical microscope image of the nickel foil used as master form (B)

In Fig. 1 (left) an AFM image of one nickel foil (A) used is shown. This nickel foil features a sinusoidal grating with a period of 0.9 µm and a peak-to-valley value (P-V) of 400 nm. The other nickel foil (B) which was used as a mould has quadratic holes with side lengths of 70 µm. The image of this nickel foil (B) was taken by an optical microscope.

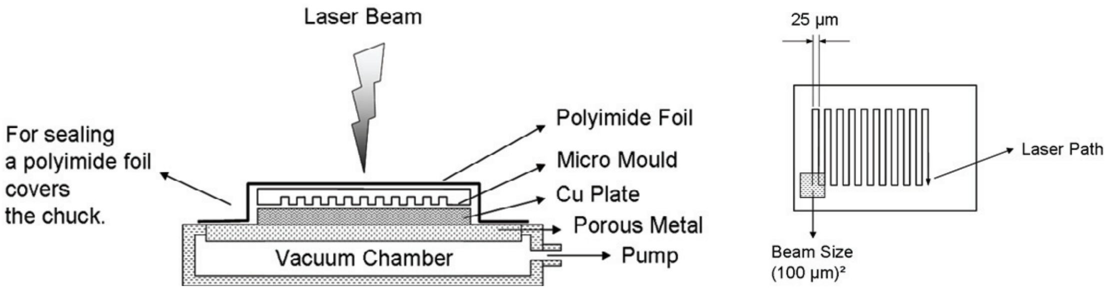

Fig. 2. (a) sketch of the experimental set-up used; (b) Scanning path of the laser beam across the workpiece during the laser embossing process

In Fig. 2 (left) the cross section of the experimental set-up is shown. First, the solid copper workpiece was placed onto a vacuum chuck. Than the nickel foil was positioned face to face with the workpiece. Finally, a 25 µm thick polyimide foil covers the vacuum chuck, the master form, and the workpiece. By turning on the vacuum the polyimide foil seals the chuck and subsequently the polyimide foil presses the nickel foil and the workpiece firmly together. Afterwards the polyimide foil was irradiated with the laser.

A KrF excimer laser with a pulse length of $t_p = 25$ ns and a wavelength of $\lambda = 248$ nm, which is embedded in a laser workstation, was used for laser irradiation. The workstation furthermore comprises a beam shaping and homogenizing optics which provides a flat top beam profile at a laser spot of A = 100 µm x 100 µm. The scanning of the laser beam across the sample surface was performed with a program-controlled x-y-z stage. The repetition rate of the laser was fixed at a value of f = 100 Hz.

Naturally, the size of the area patterned by microembossing is limited by the laser spot size. In order to show the opportunity of scaling up the presented microembossing, laser scanning processes were studied. In Fig. 2 (right) a schema of the scanning path across the sample surface can be seen whereat an overlap of 75% of parallel laser scanning lines was specified. With the formula

$$N = (L*f/v)*L/\Delta x \quad (1)$$

where N is the pulse number, L is the size of the laser spot, and Δx is the overlap between two laser scanning lines, the number of pulses which are applied onto one point can be calculated. With the given parameters the average pulse number per point is N ~ 29. With this used pulse number the polyimide foil is not drilled through and a thin polyimide layer of about 1 µm remains which is sufficient to protect the upper nickel foil from the thermal impact of the laser pulses. Therefore, after the embossing process the polyimide foil with all contaminations and debris from the laser ablation can simply be removed be taking it away. Hence, contaminations of the workpiece or the nickel master foil by debris can be excluded.

The applied laser pulses were absorbed in the polyimide foil and caused laser ablation of the polyimide foil and the formation of a plasma plume. Shock waves from the expanding plasma and thermal processes provide a momentum sufficient to emboss the structured master form into the underlying copper piece. In contrast to usual set-ups in this study no transparent confining materials (e.g. glass) were used to enhance the laser-induced pressure [4]. The pressure, which is generated by the ablation of the polyimide with a KrF laser was measured by Zweig et al. [13]. A typical laser fluence used in the present study for the laser embossing process is $\Phi = 3.5$ J/cm². From the measurements done by Zweig et al. it can be concluded that this laser fluence value generated a pressure of ~ 10^7 Pa.

3. Results and Discussion

An image of a copper surface taken with the white light interferometer after the laser embossing process is shown in Fig. 3. The structures were replicated from the nickel foil (B). It can be seen in this image that the areas in which the nickel foil (B) is perforated are higher than the surrounding area. By comparison of the resulting structures with the quadratic holes in the nickel foil (B) used as master form (Fig. 1 right) the shape of the replicated structure and the shape of the master form are in good agreement. Further, the flat smooth nickel surface results in a reduction of the surface roughness of the polished copper workpiece. Within the square openings of the master foil some remaining scratches from the polishing can be found by investigation of the workpiece surface with an optical microscope. These results show that microstructures can be successfully embossed in a solid copper surface.

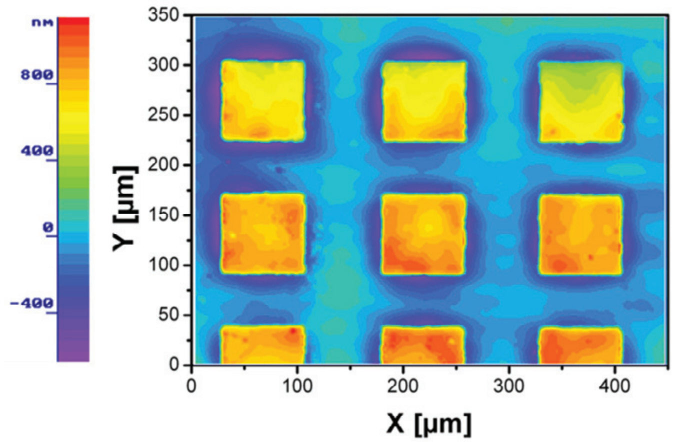

Fig. 3. Image of the copper surface taken by WLI after the laser embossing with nickel foil (B)

In order to characterise the embossing process more in detail, the height of the formed structures in dependence on the used laser fluence was investigated. In Fig. 4 the dependency of the height of the structure on the laser fluence is shown. The threshold fluence which has to be exceeded for the forming process is about 1 J/cm². After exceeding this threshold the height of the structures nearly linearly increases in dependence on the laser fluence. With the highest used fluence structure heights up to ~ 1.1 µm could be reached. However, the height of the formed structures is not limited by the nickel foil which has a thickness of 3 µm. Hence, the heights of the formed structures in the copper workpiece are determined by the used laser parameters and not by the thickness of the nickel foil which was used as master form.

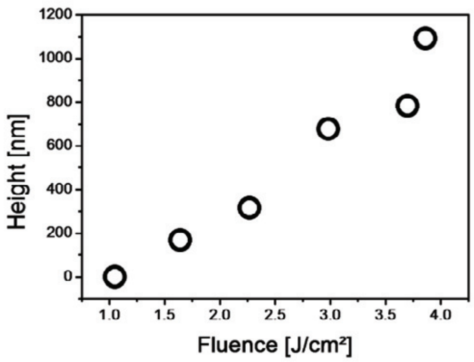

Fig. 4. Heights of the replicated structures in the copper workpiece in dependence on the used laser fluence. Nickel foil (B) was used as master form. The laser scanning speed was v = 1.4 mm/s which is equal to 29 laser pulses per point

In Fig. 5 the height of the formed structure in the copper workpiece in dependence on the applied laser pulse number is shown. The used laser fluence was fixed at a value of 3.7 J/cm². The applied laser pulse number per point was calculated from the laser scanning speed used by formula 1. It can be seen in Fig. 5 that the height of the formed structures in the copper workpiece linearly increases in dependence on the applied laser pulse number. The heights of the structures which were formed with 36 laser pulses are slightly lower than these which were formed with 29 laser pulses.

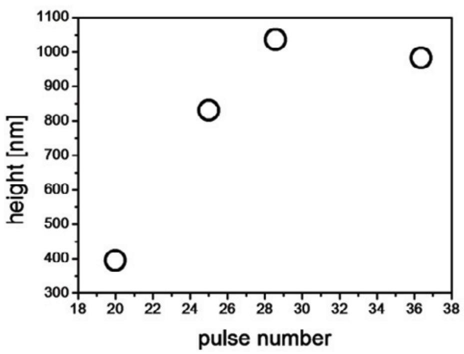

Fig. 5. Heights of the replicated structures in the copper workpiece in dependence on the applied laser pulse number. Nickel foil (B) was used as master form. The laser fluence used was F = 3.7 J/cm²

This effect can be explained by the fact that with 36 applied laser pulses per point the polyimide foil which absorbed the laser pulses is completely drilled through. The laser pulses which were applied after the polyimide foil was drilled through irradiated the nickel master foil and parts of the copper workpiece. The nickel foil has a much higher ablation threshold and a lower ablation rate than the polyimide foil. Hence, the pressure which is induced by the ablation of the nickel foil is much lower than the pressure which is induced by the ablation of the polyimide foil. In Fig. 6 the differential change in the heights of the formed structures in dependence on the applied laser pulse number is shown. From Fig. 6 it can be concluded that the differential height change of the formed structures is nearly independent from the applied pulse number as long as the polyimide foil is thick enough so that the applied laser pulses are absorbed in the polyimide foil. Hence, it can be assumed that with thicker polyimide foils higher structures can be formed into the copper workpiece because more laser pulses can be applied before the polyimide foil is drilled through.

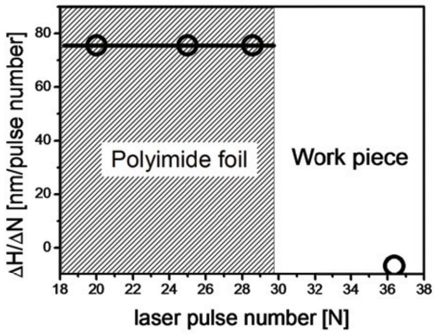

Fig. 6. Differential height changes of the formed structures in the copper workpiece in dependence on the applied laser pulse number. The shaded area indicates that the applied laser pulses are absorbed in the polyimide foil. In the blank area the laser pulse irradiated the nickel foil and parts of the copper workpiece

To study the forming characteristics in the submicrometer range the nickel foil (A) was used as master form. This nickel foil (A) shown in Fig. 1 (left) was replicated into the solid copper in an area of about $A = 10\ mm^2$. For this investigation the fluence and the scanning speed were fixed at values of $F = 3.5\ J/cm^2$ and $v = 1.4$ mm/s, respectively. In order to investigate the generated structures in the solid copper surface AFM measurements were performed. The results are shown in Fig. 7.

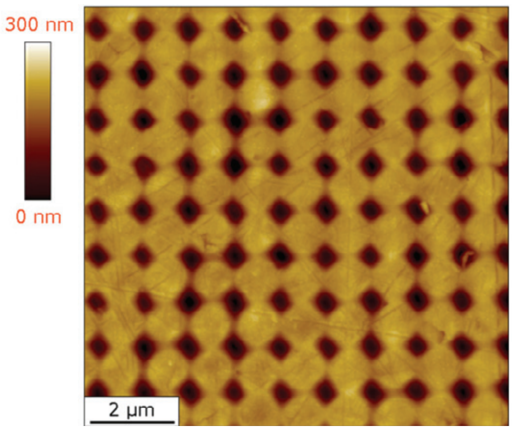

Fig. 7. AFM image of the copper surface after laser embossing with master foil (A)

It can be seen that the submicrometer pattern was successfully transferred into the solid copper. The depths of the structures are about ~ 200 nm. By comparison of the surface profile of the nickel foil (A) (shown in Fig. 1) with the surface profile of the patterned solid copper (shown in Fig. 7) it is obvious that the replicated structures differ from the master structure in the nickel foil (A). The top view of the structure from the master form (A) shows wave-like patterns of a nearly 3D sine structure. The correspondent embossed structure in the copper surface appears as square pyramids. The corners of that square structure are aligned in that way that the corner of one pyramid is facing the corner of the next pyramid. In Fig. 8 a depth profile of the master structure and the correspondent embossed structure taken by AFM are shown. From this image it can be seen that only the peaks from the master structures are properly replicated into the copper surface and in those areas, where the valleys of the master structures are, no changing of the surface of the copper can be seen. The scratches which can be seen in Fig. 7 (right) in these areas are caused by the polishing procedure of the workpiece and they are not affected by the embossing process.

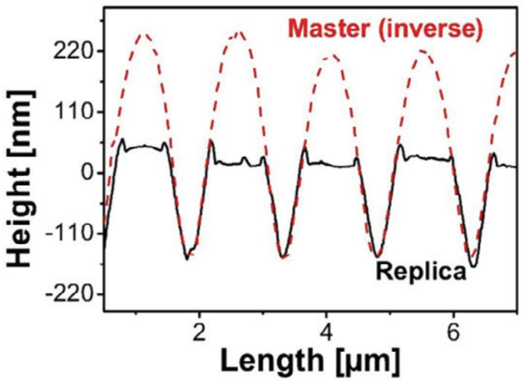

Fig. 8. Depth profile of the inverse master form (nickel foil (A), Fig. 1) and the replicated structures in the copper workpiece (Fig. 7) – measured with AFM

From the shown depth profiles in Fig. 8 it can be seen that the depths of the replicated structures have values of about 200 nm which is less than the 400 nm of the master structures. However, by comparison of the depth profiles of the master and the replicated structures in Fig. 8 it can be deduced that despite of the differences in the shape and height of the replicated structures in comparison to the master structures the inverse master fits the surface topography of the replica very well. The processed area of A = 10 mm² is much larger than the spot size of the laser beam (100 µm x 100 µm) used. However, no superstructures could be seen at the processed sample which may be caused by the laser scanning mode.

To investigate the stability of the structures of the master foil (A), the same area of the nickel foil (A) was embossed five times in different areas of the solid copper sample. Subsequently, all five formed patterns were characterised by AFM. By comparison of these five patterns no changes in the depth or shape of the formed structures could be detected. From that it can be concluded that the stability of the applied master form is sufficient for repeatedly usage.

4. Summary

Laser embossing of solid copper pieces with nickel foils as master form were investigated. Micro- and submicrometer structures were successfully transferred from nickel foils as master forms into copper workpieces. Although laser scanning was used to extend the processed area no superstructures which may result from the overlap of the laser scans could be found in the embossed patterns. The structure of the inverse master form fits the replica in the copper surface well.

The heights of the replicated structures in the copper surface linearly increase in dependence on the used laser fluence and the applied laser pulse number. In the case of the replication of submicrometer sinusoidal gratings the replicated structures differ from that of the used master form. The “round” structures of the master form appear in the replicated copper surface as quadratic pyramids.

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