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Over-plating 工艺过程的变网格数值模拟

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摘要：考察了 over-plating 工艺中不同线距、线宽条件下的电沉积规律。利用数值模拟方法对图形结构轮廓和电沉积速度之间的相互影响进行了分析，同时采用变网格方法来适应电沉积过程中结构轮廓的不断变化。数值模拟结果表明：当线距/线宽较大（>12）时，相邻图形的电沉积速度受到的影响很小，图形的横向和纵向的电沉积速度逐渐趋于一致；而当线距/线宽较小（<6）时，相邻电沉积图形之间相互影响显著，线距/线宽越小，纵向电沉积速度和横向电沉积速度之比越大，因此相邻电沉积图形中间区域可能产生空洞，从而出现电镀缺陷的情形。对于上述工艺缺陷，可以通过增加辅助导电层进行消除，实验结果表明效果良好。

关　键　词：over-plating；UV-LIGA；变网格；模具
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Numerical simulations on over-plating by deformed meshes

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Abstract: The electrical deposition in an over-plating technology was explored under different line spaces and line widths and the effect of geometries, such as a line space/line width ratio, and the deposition velocity during the over-plating was investigated by using numerical simulations. Then, the deformed meshes were also applied to suit to the boundary grows of plated microstructure with the deposition. The numerical results indicate that the difference of deposition velocity between the two adjoined plating lines is small and the depositing velocitie of the lateral and vertical directions are almost the same when the ratio of line space to line width is larger than 12. But the depositing in lateral direction will be constrained when the ratio of line space to line width is smaller than 6. The deposition can stop in a hole between the two plated lines and can cause the plating defect, for the smaller the line space/line width is, the bigger the ratio of leteral deposition velocity to vertical deposition velocity is. Experiments also show that the plating defect mentioned above can be removed by a technical method using a second seed layer on photoresist.

Key words: over-plating; UV-LIGA; deformed mesh; mold insert

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1 Introduction

UV-LIGA process is one of the most important bulk fabrication methods with a high aspect ratio for polymers based MEMS devices[1-3], which combines the ultraviolet lithography, electroforming, and molding process. The main task of electroforming process is to obtain a high quality metal monolithic mold insert which enables a low cost and a mass production of polymer based MEMS devices[4-6]. The challenge for electroforming is how to completely transfer the pattern from the photo-resist microstructure under the coupling of multi-field during plating.

The over-plating is a key stage to fabricate the monolithic mold insert in a electroforming process from the UV-LIGA technology. Due to the coupling between the plated layer shape and the depositing velocity during over-plating, the actual plated shape usually deviates from the design. Recent researchers have observed that the geometry of plating pattern, such as a line width and a spacing, usually affects the over-plating process, especially a ratio of large space to linewidth of the microstructure. Guo[7] found that a typical defect of hole-formation occured at the top of an electroplated metal mold due to the large ratio of microstructure, and suggested the ratio of space to linewidth should be no more than 7. But in fact, the ratio in most microfluidics, such as capillary electrophoresis microchip, is really large, usually tens or hundreds, which is a disaster for conventional over-plating. Thus Luo[8] and Lv[9] simplified the electroforming process by depositing the metal structure directly onto a metal plate, instead of conventional electroforming. By this method, a whole metal mold inserts were obtained. Unfortunately, the juncture between the deposited microstructure and the metal plate is relative weak, which usually reduced the lifetime of mold insert in a molding process. On the contrary, Zhu[6] improved the conventional over-plating process using a second electric layer to reduce the effective ratio of line space to linewidth, and obtained a monolithic mold insert as that in the conventional electroforming process. These previous research on over-plating mainly focused on technical solution[10].

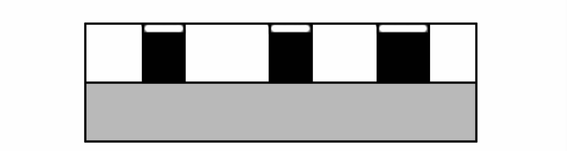
One solution to this problem is to amend the design according to these coupling effects so that the whole top surfaces of photo-resist can be fully covered with a deposited metal layer before back-plating. It is necessary to investigate the principle of the over-plating with different geometries such as line space/linewidth ratio.

With the development of computer technology, it is possible to numerically simulate the electroforming process using Finite Element Method (FEM). But in this case, the core problem in the FEM of such over-plating is that the boundaries of plated layers are moved in time and with the depositing velocity. There are usually two solutions to this problem: one is remeshing[11], the other is using deformed meshes, especially when the boundaries of the computational domain are moved in time or as a function of a parameter[12]. Especially the arbitrary Lagrangian Eulerian (ALE) method is mostly used for the deformed meshes. In consideration of the outstanding performance and computing velocity of the ALE, the later method is chosen in this paper.

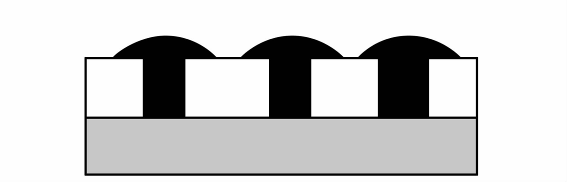
This work mainly investigates the numerical simulation of over-plating with different geometries such as space/linewidth ratio by deformed meshes.

2 Numerical simulation

The conventional electroforming process, as shown in Fig. 1, consists of three stages: 1) aspect ratio preserved plating that fills the photo-resist cavity; 2) over-plating which the metal grows along the surface of photo-resist and covers all the surface; 3) back-plating which forms a thick metal substrate. The first and third stages are connected by over-plating. The basic characteristic of over-plating is that the profile of plated structure is affected by the coupling between the plated structure and the depositing velocity. In this part, numerical simulation is used to investigate this process.



(1) Plating



(2) Over-plating

(3) Back-plating

Fig. 1 Sketch map of electroforming for conventional UV-LIGA process

2.1 Electroplating theory

The plating theory is a complex engineering issue with many factors such as electric fields, fluid dynamics, electrochemical kinetics, heat transfering and so on. The equations lie on the plating process. In order to simplify this problem, the simulated process is restricted as follows: 1) the current density is normal to a deposition surface; 2) the current efficiency is assumed to be 100%; 3) the initial shape of plating line is considered as a semicircle due to the almost isotropic deposition at the beginning of the over-plating; 4) The process is adiabatic which means no heat is transferred when the flow field and the temperature is constant; 5) all the simulations are presumed in the absence of bath stirring; 6) considering the distance between two electrodes is large compared to the plating dimension, the flow field is in steady state, and the mass transfer is sufficient, then the flow equations are ignored.

Thus, the process of over-plating is determined by the electric field of the electrolyte and the depositing kinetics. So the basic equations for the over-plating just consist of an electro field equation and a depositing velocity equation.

(1) Depositing velocity

The over-plating usually results in a moving boundary because when the geometry changes the current density distribution changes with it correspondingly. A simple model for the deposition is based on the assumption that the deposition rate is proportional to the normal current density J_n at the surface. The velocity u in the direction of the mesh normal at the electrode surface then becomes

$$u = K \cdot J_n, \tag{1}$$

Where K is the coefficient of the proportionality.

(2) Electric field in electrolyte

The electric field equation for electrolyte is given by Gauss's law:

$$\nabla \cdot (\varepsilon E) = \rho , \tag{2}$$

where $E = -\nabla V$, ε is permittivity, ρ is charge density, V is electric potential in electrolyte.

(3) Current density

The current density J between the anode and the plating sample is stated as Ohm's law:

$$J = \sigma E + J^e, \tag{3}$$

Where σ is electrolyte's electrical conductivity, J^e

is an externally generated current density, in this model, the J^e is set to 0.

2.2 Boundary conditions

In this simulation, the two 2-D modes are used including the Conductive Media DC and transient Moving Mesh (ALE) applications modes. Boundary conditions for the former (corresponding to electric field in media) mainly consist of the anode, bath wall and cathodes. The electric potential of the anode is 1.5 V, the bath wall is electric insulation, and the cathodes are grounded. The boundary conditions for the ALE are shown in section 2.4.

2.3 Electrolyte system of simulated model

The model geometry of over-plating consists of 7 cm×8 cm rectangular electrolyte bath with nickel cathode(s) to be plated, and an anode covering the whole top of the bath. The linewidth of anode is 80 μm, the space between the two cathodes varies from 120 μm to 960 μm. The electrical conductivity of electrolyte is set as 10 S/m. The electric potential of the anode is 1.3 V.

Due to high deposition rate and low inner stress, the nickel sulfamate electrolyte is usually used in UV-LIGA, and also used in this work for experiment. The composition of the electrolyte is shown as in table 1. The pH of the electrolyte is adjusted to 3～4 by buffer solution.

Tab. 1 Composition of nickel electrolytic solution

Components	Quantity
$Ni(SO_3NH_2)_2\ 4H_2O$	330 g/L
$NiCl_2 6\ H_2O$	40 g/L
H_3BO_3	50 g/L
Wetting agent	1-2 mL/L

2.4 Numerical simulation

In this work, the numerical simulation is performed in FEM analysis software of FEMLAB (COMSOL Multiphysics, Version 3.2) and Matlab (MathWorks Inc, Version 6.5). Similar to the electric field mode, the moving mesh application mode needs boundary conditions, too. For the anode and bath wall, the mesh displacement dx and dy are both set to 0. The normal and tangent mesh velocities for the cathodes are set to u and 0 respectively. The y-direction mesh velocity for the substrates is set to 0.

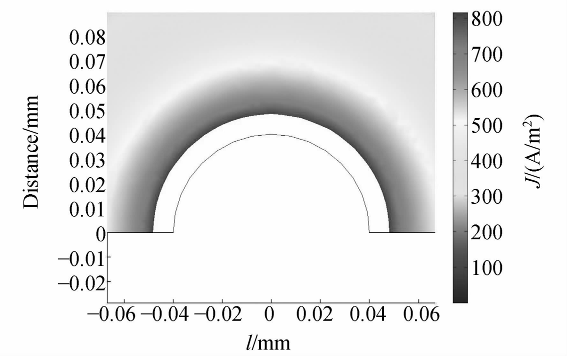
3 Results and discussion

3.1 Numerical simulation

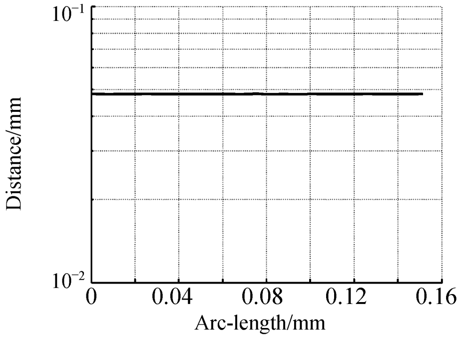
For single line over-plating model, this simulation will focus on the depositing velocity in lateral direction and vertical direction. The initial line shapes of the two cases are supposed as semicircular and tabular, respectively. The linewidth and radius of semicircular line are 80 μm and 40 μm. The linewidth and height of the latter are 100 μm and 10 μm. The deposition rate on the surface of single semicircle line keeps uniform in time, as shown in Fig. 2(a). Then the distance from the central of the line to the point on the deposited shape is kept uniform too, as seen in Fig. 2(b). The results indicate that the deposition rate for single semicircle line is isotropic.

For the tabular line, the depositing velocity in lateral direction is more than that of the vertical direction, as shown in Fig. 2(c). But the vertical depositing velocity increases in time, which means that the difference of depositing velocity between the lateral and vertical directions reduces with the trend of shaping semicircular line (Fig. 2d).

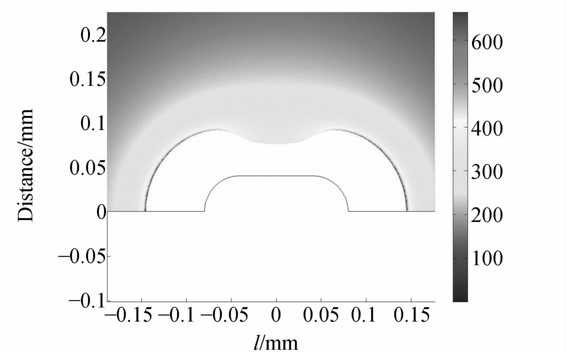
It can be seen that single line in the over-plating has the trend of shaping semicircular line because the difference of depositing velocity between the lateral and vertical directions reduces in time due to no confinements from other lines.



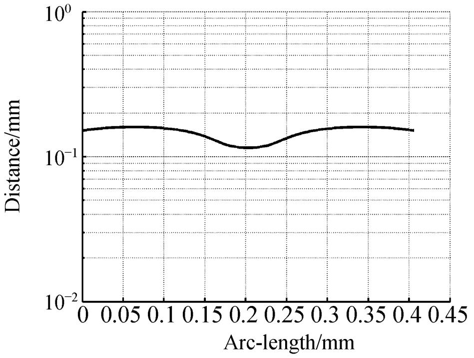
(a) Shape of deposited line after over-plating



(b) Distance from the central of line to the point on deposited shape



(c) Shape of deposited line after over-plating

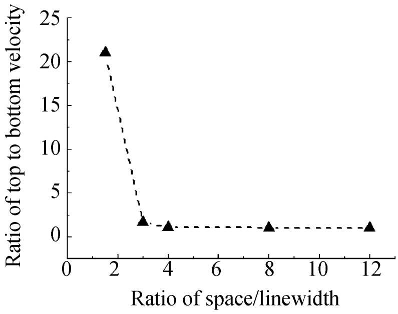


(d) Distance from the central of the line to the point on deposited shape

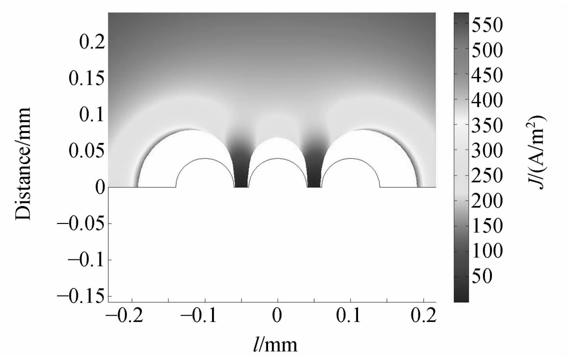
Fig. 2 Process of over-plating for single line

3.2 effect of line space/width ratio on over-plating

Due to the coupling between the line shape and the depositing velocity, the line space/width ratio will affect the process of over-plating. In this work, it is characterized by the ratio of depositing velocity on top and bottom of the line. The results indicate that when the line space/width ratio decrease, the depositing velocity reduces in lateral direction due to the interaction between the near plated shape and the electric field, as shown in Fig. 3(a). The deposition velocity in lateral direction almost stops for the ratio of 0.25 as in Fig. 3(b). Thus, the smaller of space/line width ratio means more restrained depositing in lateral direction, even a hole may formed between the two near lines[7]. The re-



(a) Effect of space/width ratio on difference of depositing velocity on top and bottom of line



(b) Depositing velocity in lateral direction almost stops for the ratio of 0.25

Fig. 3 Line space/width ratio effect on over-plating sults also indicate that there is a little difference of depositing velocity between the lateral and vertical directions when the space/line width ratio is more than 8. But along with the depositing, the ratio of space to line width also reduces. In conclusion, the close plating lines will restrain the lateral depositing velocity with the results of extending the over-plating stage, even forming a defect during the over-plating. The simulation results suggest that this problem needs additional ways for solution.

3.3 Optimized over-plating process

In order to avoid the problem caused by the ratio of large space/line width, a second seed layer is sputtered on the top surface of the photoresist layer using a mask, the detail process can be seen as in previous work[6]. By this way, the back-plating stage can quickly start when the over-plated metal connects to the second seed layer. The SEM of the mold insert fabricated by modified UV-LIGA process is shown as in Fig. 4. The result indicates that the restraining of the lateral depositing velocity can be solved by this technical method.

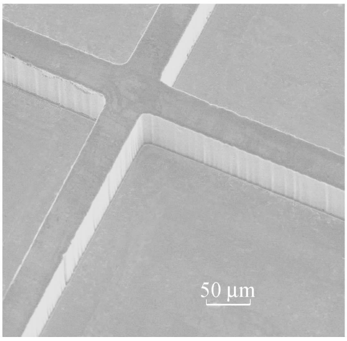


Fig. 4 SEM of nickel mold insert by optimized electroforming process

4 Conclusions

Over-plating in UV-LIGA is under the coupling between the shape of deposited line and the depositing velocity. For single plated line, the difference of depositing velocity between the lateral and vertical direction reduces until shaping semicircular line due to no constrain from other nearby plating line. But for close lines, depositing in lateral direction will be constrained for a small ratio of line space/width. This defects caused by over-plating can be solved by the technical method using a second seed layer on photoresists.

References:

[1] BECKER E W, EHRFELD W, MANER A, *et al.*. Fabrication of microstructures witht high aspect ratios and great structural heights by synchrotron radiation lithography, galvanoforming and plastic molding (LIGA process)[J]. *Microelectronics*, 1986(4):35-36.

[2] SHAO L, DU L, WANG L. Study on electrode process of UV-LIGA micro-electroforming by AC impedance method[J]. *Opt. Precision Eng.*, 2007,15(7):1047-1053. (in Chinese)

[3] MING P M, ZHU D, HU Y Y, *et al.*. Fabrication of nickel soft contact microprobe based on UV-LIGA[J]. *Opt. Precision Eng.*, 2007,15(5):735-740. (in Chinese)

[4] DU L Q, LIU H J, QIN J, *et al.*. Study on uniformity of micro-electroformed device[J]. *Opt. Precision Eng.*, 2007,15(1):69-75. (in Chinese)

[5] HECKEL M, BACHE W, MULLER K D. Hot embossing - the molding technique for plastic microstructures[J]. *Microsyst. Technol.*, 1998(4):122-124.

[6] ZHU X L, LIU G, XIONG Y, *et al.*. Fabrication of PMMA microchip of capillary electrophoresis by optimized UV-LIGA processes [J]. *Journal of Physics: Conferences Series*, 2006,34:875-879.

[7] GUO Y H, TIAN Y C, DU R. On the design and fabrication of metal molds in LIGA [C]. *Proceedings of 3thd IEEE Int. Conf. on Nano/Micro Engineered Molecular Systems. Sanya, China*, 2008:

990-995.

[8] LUO, Y CHU D N, LOU Z F, *et al.*. Using electro-deposition to fabricate mould for polymer microfluidic chip[J]. *Electrochemistry*, 2005,11(2): 204-207.

[9] LV C H, YIN X F, LU P. A simplified Microfabrication technology for production of Nickel mold insert for replicating of plastic microfluidic chips [J]. *Chinese Journal of Analytical Chemistry*, 2007,35(5):767-771. (in Chinese)

[10] ZHU X L, GUO Y H, LIU G, *et al.*. Non-planar electroforming of microfluidic mold insert [J]. *Journal of Functional Materials and Devices*, 2008,14(2):417-421. (in Chinese)

[11] GELTEN C J M, KONTER A W A. *Application of mesh rezoning in the updated Lagrangian method to metal forming processes, in J. F. Pittman et. al.* [M]. Numerical Methods in Industrial Forming Processes, Swansea UK: Pineridge Press, 1982.

[12] COMSOL(3.2)TM Multiphysics Modeling Guide, p303-310, 2005[Z].

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