内含四棱台空腔电磁辅助转印印戳的力学模型

于庆民*, 陈福荣, 周红磊, 余旭东

西北工业大学力学与土木建筑学院, 西安 710129

* 通信作者. E-mail: qingminyu@163.com

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摘要 转印是柔性可延展电子器件制备的重要手段, 而对印戳与元件界面作用力的调控是转印技术的关键. 本文提出了一种内含四棱台空腔结构的电磁辅助转印印戳并建立了该印戳的力学模型. 在交变电磁场作用下, 印戳上部的磁性薄膜发生凹凸变形并通过空腔内封装的液体传递给底部的柔性薄膜, 从而改变印戳底部空腔缺陷处的压力大小, 实现对印戳和电子元件间作用力的调控. 力学分析表明, 该印戳在转印过程中底部开口空腔缺陷处压力变化的大小随着电磁驱动压力的增大而增大, 而随着薄膜弹性模量、薄膜厚度、薄膜的边长比的增大而减小. 印戳薄膜边长比、厚度、弹性模量越小, 对转印越有利.

关键词 电磁辅助转印, 印戳, 力学模型, 四棱台空腔, 有限元分析

1 引言

转印 (transfer printing) 是指将微纳尺度材料或元件集成为空间有序的二维或三维功能模块^[1], 是可延展柔性电子器件制备的关键技术. 转印过程可分为上墨和印刷两个阶段. 在上墨过程中, 利用柔性印戳 (常用柔性聚合物如聚二甲基硅氧烷 (PDMS) 来制备) 将在赠体上蚀刻好的所需电子元件 (一般是薄膜材料) 从赠体上撕起; 在印刷过程中, 通过印戳将这些元件放置在受体上的合适位置, 从而构成功能器件^[2]. 这种技术能够行之有效地将独立制备、不同种类的离散器件进行大规模集成, 进而形成空间有序的功能系统, 如 GaAs 激光器^[3]、太阳能电池^[4]、多孔硅微腔^[5]、发光二极管^[6]、可调焦仿生电子眼^[7]等.

转印过程中主要涉及印戳/元件和元件/基体 (赠体和受体) 两个界面的“竞争断裂”^[8]. 印戳/元件界面的粘附作用在上墨过程中需大于元件/赠体界面的粘附作用, 在印刷过程中要小于元件/受体界面的粘附作用, 才能顺利完成转印. 如何恰当地解决粘附作用强–弱转化这一矛盾问题是转印技术中面临的主要挑战. 因此, 对于印戳与元件界面粘附的调控是转印技术的关键.

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图 1 (网络版彩图) 内含四棱台空腔的电磁辅助转印印戳

Figure 1 (Color online) Electromagnetic-assisted transfer printing stamp with a four prism cavity. (a) The stamp structure; (b) the deformation of stamp during printing; (c) the deformation of stamp during pickup

目前常采用化学的方法^[9,10]和基于力学的方法^[8,11~18]来实现对界面粘附的调控. 由于基于力学的转印过程对元件和基体没有损害, 不会影响元件的电学性能, 因此成为转印技术领域的一个主要研究方向. 迄今为止, 在柔性电子器件制备中得到应用的转印技术主要有以下几种: (1) 运动控制转印^[8,11], 通过控制剥离速度实现控制粘附强度的目的; (2) 印戳表面结构辅助转印^[12,13], 通过在印戳表面设计精巧结构来调整印戳与元件之间的接触面积, 从而达到控制粘附强度的目的; (3) 载荷辅助转印^[14~16], 在转印中对印戳施加横向剪切载荷, 可以使印戳/元件界面边缘产生分离, 从而可以减小印刷时印戳与元件间的粘附力; (4) 激光辅助转印^[17], 在印刷过程中通过透明印戳施加激光脉冲, 利用印戳和元件间产生的不协调热应力促使印戳/元件界面率先开裂; (5) 基于形状记忆聚合物的转印^[18], 通过改变温度来控制形状记忆聚合物印戳表面设置的微结构的形态, 从而实现调控界面粘附作用的目的. 以上方法中, 方法(1)~(3)借助于印戳的材料特性或者结构特点以及载荷特点来调控界面粘附作用, 属于被动转印方法, 尽管可以完成转印, 但不利于转印成功率的提高. 方法(4)和(5)通过外加激励改变界面粘附作用, 属于主动转印方法, 但由于采用了温度控制策略, 导致转印效率低、控制精度差, 如采用水凝胶智能材料作为印戳, 完成一个转印过程需要 90 min^[19]. 因此, 发展一种准确、高效、控制简便的转印方法, 是可延展柔性电子器件制备面临的重要科学问题.

如图 1(a) 所示, 本文提出的新型转印印戳具有四棱台型密闭空腔结构, 内充液体, 以磁性复合薄膜作为驱动器, 在交变电磁场的作用下, 四棱台空腔上下表面柔性薄膜发生凹凸变形. 在上墨过程中

(图 1(b)), 由于磁场的作用, 使得四棱台空腔上下表面薄膜向上凸起, 印戳底部缺陷处和元件之间会形成一负压区, 从而有助于元件的拾取; 印刷过程中 (图 1(c)), 由于反向磁场的作用, 四棱台空腔上下表面柔性薄膜向下凸起, 增大印戳底部缺陷处的压强, 从而使元件容易从印戳上剥离. 通过施加交变电磁场, 主动控制元件和印戳空腔缺陷处的压力变化, 从而实现界面粘附的调控和可逆性, 因此这种转印方法可称为电磁辅助主动控制转印. 本文通过理论分析建立了该印戳底部空腔处的压力变化和电磁驱动薄膜所受电磁驱动力之间的力学模型, 并通过有限元分析验证了该模型的有效性, 结果将对柔性电子电磁辅助转印提供理论指导.

2 印戳力学模型的建立

2.1 印刷过程

印戳结构中, 电磁驱动部件是以 PDMS 为基底、磁性纳米颗粒^[20,21] (例如坡莫合金颗粒或者磁性氧化铁 Fe_3O_4 颗粒等) 为填充物, 两者充分混合固化而成的磁性薄膜, 在电磁场作用下发生变形从而直接驱动密封液体流动. 如图 1(a) 所示为含四棱台型密闭空腔结构的印戳示意图, 上、下表面薄膜的边长别为 a_{top} 和 a_{bot} , 厚度均为 h , 印戳底部开口空腔的高度为 h_c 、壁厚为 L . 假设磁性薄膜在径向方向上的磁化强度忽略不计, 只考虑其在 Z 轴方向上的磁化强度, 则磁性薄膜在磁场作用下受到的总磁力 F 为^[22~24]

$$F = \mu_0 V_{\text{mag}} \frac{\Delta H}{\Delta Z} M_Z, \quad (1)$$

其中 $\mu_0 = 4\pi \times 10^{-7} \text{ Tm/A}$ 为自由空间磁导率, V_{mag} 为磁性薄膜的体积, $\Delta H = H_{Z1} - H_{Z2}$, H_{Z1} , H_{Z2} 分别为磁性薄膜上部和底部在 Z 方向上的磁场强度, M_Z 为 Z 方向磁化强度. 对于边长为 a_{top} 的正方形电磁驱动薄膜, 在单位面积上受到的压力为

$$\Delta p = \frac{F}{a_{\text{top}}^2} = \mu_0 \frac{\Delta H V_{\text{mag}}}{\Delta Z a_{\text{top}}^2} M_Z. \quad (2)$$

在印刷的过程中, 含四棱台型空腔电磁辅助转印印戳的磁性薄膜向下的位移场为^[25]

$$w_{\text{top}}(X, Y) = w_{\text{top}}^{\max} \left(1 - 4 \frac{X^2}{a_{\text{top}}^2} \right)^2 \left(1 - 4 \frac{Y^2}{a_{\text{top}}^2} \right)^2, \quad (3)$$

下层 PDMS 薄膜的位移场为^[25]

$$w_{\text{bot}}(X, Y) = w_{\text{bot}}^{\max} \left(1 - 4 \frac{X^2}{a_{\text{bot}}^2} \right)^2 \left(1 - 4 \frac{Y^2}{a_{\text{bot}}^2} \right)^2, \quad (4)$$

其中 $w_{\text{top}}^{\max}$ 和 $w_{\text{bot}}^{\max}$ 分别为上部磁性薄膜和下部 PDMS 薄膜的最大位移 (图 1(b) 和 (c)). 在电磁场的作用下, 上、下层薄膜由于变形引起的体积变化必须相等^[26], 即

$$\begin{aligned} & \int_{-\frac{a_{\text{top}}}{2}}^{\frac{a_{\text{top}}}{2}} \int_{-\frac{a_{\text{top}}}{2}}^{\frac{a_{\text{top}}}{2}} w_{\text{top}}^{\max} \left(1 - 4 \frac{X^2}{a_{\text{top}}^2} \right)^2 \left(1 - 4 \frac{Y^2}{a_{\text{top}}^2} \right)^2 dX dY \\ &= \int_{-\frac{a_{\text{bot}}}{2}}^{\frac{a_{\text{bot}}}{2}} \int_{-\frac{a_{\text{bot}}}{2}}^{\frac{a_{\text{bot}}}{2}} w_{\text{bot}}^{\max} \left(1 - 4 \frac{X^2}{a_{\text{bot}}^2} \right)^2 \left(1 - 4 \frac{Y^2}{a_{\text{bot}}^2} \right)^2 dX dY. \end{aligned} \quad (5)$$

由式 (3)~(5) 可以得到

$$w_{\text{bot}}^{\max} = k^2 w_{\text{top}}^{\max}, \quad (6)$$

其中 k 为印戳空腔处下部和上部薄膜的边长比, 即

$$k = \frac{a_{\text{bot}}}{a_{\text{top}}}. \quad (7)$$

在转印中, 印戳系统的能量由上、下层薄膜的应变能 (U_{top} 和 U_{bot}) 和外力做功 ($U_{\Delta p}$) 组成

$$U_{\text{total}} = U_{\text{top}} + U_{\Delta p} + U_{\text{bot}}. \quad (8)$$

上层薄膜的变形能为^[25]

$$U_{\text{top}} = \int_{-\frac{a_{\text{top}}}{2}}^{\frac{a_{\text{top}}}{2}} \int_{-\frac{a_{\text{top}}}{2}}^{\frac{a_{\text{top}}}{2}} \left\{ \frac{E_{\text{top}}^2}{24(1-\nu_{\text{top}}^2)} \left(\frac{\partial^2 w_{\text{top}}}{\partial X^2} + \frac{\partial^2 w_{\text{top}}}{\partial Y^2} \right) + \frac{h}{8} \frac{E_{\text{top}}}{1-\nu_{\text{top}}^2} \left[\left(\frac{\partial w_{\text{top}}}{\partial X} \right)^4 + \left(\frac{\partial w_{\text{top}}}{\partial Y} \right)^4 \right] \right\} dXdY, \quad (9)$$

下层薄膜的变形能为^[25]

$$U_{\text{bot}} = \int_{-\frac{a_{\text{bot}}}{2}}^{\frac{a_{\text{bot}}}{2}} \int_{-\frac{a_{\text{bot}}}{2}}^{\frac{a_{\text{bot}}}{2}} \left\{ \frac{E_{\text{bot}}^2}{24(1-\nu_{\text{bot}}^2)} \left(\frac{\partial^2 w_{\text{bot}}}{\partial X^2} + \frac{\partial^2 w_{\text{bot}}}{\partial Y^2} \right) + \frac{h}{8} \frac{E_{\text{bot}}}{1-\nu_{\text{bot}}^2} \left[\left(\frac{\partial w_{\text{bot}}}{\partial X} \right)^4 + \left(\frac{\partial w_{\text{bot}}}{\partial Y} \right)^4 \right] \right\} dXdY, \quad (10)$$

其中 E_{top} , E_{bot} 分别为磁性薄膜和底部薄膜的弹性模量, ν_{top} , ν_{bot} 分别为 Poisson 比.

在印刷中印戳底部开口空腔缺陷处的体积变化大小为

$$\Delta V_c = V_{c0} - V_c = \frac{64}{225} a_{\text{bot}}^2 w_{\text{bot}}^{\text{max}}, \quad (11)$$

其中 $V_{c0} = a_{\text{bot}}^2 h_c$ 为印戳下层薄膜无变形时底部开口空腔缺陷处的初始体积, $V_c = a_{\text{bot}}^2 (h_c - 64w_{\text{bot}}^{\text{max}}/225)$ 为下层薄膜变形后印戳底部开口空腔缺陷处的体积.

印刷过程中外力所做的功为

$$U_{\Delta p} = \int_0^{\Delta V_c} \Delta p_c d\Delta V_c - \int_{-\frac{a_{\text{bot}}}{2}}^{\frac{a_{\text{bot}}}{2}} \int_{-\frac{a_{\text{bot}}}{2}}^{\frac{a_{\text{bot}}}{2}} w_{\text{bot}}(X, Y) \Delta p_c dXdY, \quad (12)$$

其中底部开口空腔缺陷处的压强变化大小 Δp_c 为

$$\Delta p_c = \frac{\Delta V_c}{V_{c0} - \Delta V_c} p_{c0} = \frac{64w_{\text{bot}}^{\text{max}}}{225h_c - 64w_{\text{bot}}^{\text{max}}} p_{c0}, \quad (13)$$

式中 p_{c0} 为印戳开口空腔处的初始压强 (取标准大气压值). 则印戳系统的总能量为

$$\begin{aligned} U_{\text{total}} &= U_{\text{top}} + U_{\Delta p} + U_{\text{bot}} \\ &= \frac{64 \times 2^9 h^3}{75 \times 49} \left[\frac{\bar{E}_{\text{top}}(w_{\text{top}}^{\text{max}})^2}{a_{\text{top}}^2} + \frac{\bar{E}_{\text{bot}}(w_{\text{bot}}^{\text{max}})^2}{a_{\text{bot}}^2} \right] \\ &\quad + \frac{64 \times 2^{28} h}{75 \times 63 \times 121 \times 169 \times 17} \left[\frac{\bar{E}_{\text{top}}(w_{\text{top}}^{\text{max}})^4}{4a_{\text{top}}^2} + \frac{\bar{E}_{\text{bot}}(w_{\text{bot}}^{\text{max}})^4}{4a_{\text{bot}}^2} \right] \end{aligned}$$

$$-\frac{64}{225}\Delta p_c a_{\text{bot}}^2 w_{\text{bot}}^{\max} - \frac{64}{225}p_c a_{\text{bot}}^2 \left[w_{\text{bot}}^{\max} - \frac{225}{64}h_c \ln \left(\frac{225}{64}h_c - w_{\text{bot}}^{\max} \right) \right]. \quad (14)$$

由最小势能原理可以得到

$$\Delta p = \frac{3hw_{\text{bot}}^{\max}}{a_{\text{bot}}^2} \left[20.9(1 + \lambda k^6)\bar{E}_{\text{bot}} \frac{h^2}{a_{\text{bot}}^2} + 12.3(1 + \lambda k^{10})\bar{E}_{\text{bot}} \frac{(w_{\text{bot}}^{\max})^2}{a_{\text{bot}}^2} \right] + \frac{64w_{\text{bot}}^{\max}}{225h_c - 64w_{\text{bot}}^{\max}}p_{c0}, \quad (15)$$

其中 $\lambda = \bar{E}_{\text{top}}/\bar{E}_{\text{bot}}$ 为上、下层薄膜的平面应变模量比, $\bar{E}_i = E_i/(1 - \nu_i^2)$ ($i = \text{top}, \text{bot}$). 这个公式建立了印刷过程中印戳底部薄膜的最大位移 $w_{\text{bot}}^{\max}$ 与磁性薄膜在电磁场作用下产生的电磁驱动压力 Δp 之间的关系, 与上下层薄膜的弹性参数、边长比和厚度有关.

为了验证式 (15) 的正确性, 采用有限元方法进行了模拟. 采用 SPH (smoothed particle hydrodynamics) 方法来模拟流固耦合作用, 空腔缺陷采用 cavity radiation 的相互作用约束, 在预定义场中对印戳缺陷处施加的 fluid cavity pressure 压强为标准大气压强 0.1 MPa. 印戳空腔封装的液体为水, 其声速为 1483 m/s, 粘度为 0.001 kg/ms, 密度为 1000 kg/m³. 假设上、下层薄膜的弹性模量相同, 取值范围为 0.65~2 MPa, Poisson 比均为 0.45. 为了简化计算, 不考虑电磁场的作用, 而以作用在磁性薄膜上的均布压力表示电磁驱动力. 有限元模型全部使用三维八节点减缩积分单元, 流体部分进行了粒子化处理.

图 2 所示为印刷过程中下层 PDMS 薄膜的最大变形量 $w_{\text{bot}}^{\max}$ 与电磁驱动压力 Δp 的关系, 有限元和理论结果基本一致. 薄膜厚度不同的情况下, 如图 2(a) 所示, 下层 PDMS 薄膜最大位移随着电磁驱动压力的增大而增大, 随着薄膜的厚度增大而减小. 当电磁驱动压力 $\Delta p = 0.02$ MPa, 薄膜厚度分别为 0.65, 0.8, 1 mm 时, 相应的理论和有限元结果大致为 1.4, 1.0, 0.95 mm, 说明当电磁驱动力 Δp 相同时, 薄膜厚度越小, 下层薄膜的 $w_{\text{bot}}^{\max}$ 越大. 如图 2(b) 所示, 上、下层薄膜的边长不同时, 下层薄膜最大位移随着电磁驱动压力的增加而增大, 在相同电磁驱动力作用下, 边长比越小的下层薄膜产生的位移越大. 同样地, 下层薄膜最大位移随着电磁驱动压力的增加而增大, 当电磁驱动力 Δp 相同时, 薄膜的弹性模量越大, 下层薄膜最大变形越小 (图 2(c)). 这说明当薄膜的厚度、边长比和弹性模量越小时, 下层薄膜的位移越明显.

由于印戳底部开口空腔内的压强变化与下层薄膜的变形相关, 下层薄膜的变形越大, 开口空腔处的体积变化就越大, 相应的压强变化就越明显, 越有利于印戳功能的实现. 图 3 给出了边长比不同时印戳底部开口缺陷处的压强变化大小 Δp_c 与电磁驱动压力 Δp 之间的关系. 缺陷处压强变化的大小随着电磁驱动压力增大而增大, 并且随着电磁驱动压力增大的速率逐渐减小; 边长比越小的印戳, 缺陷处压强变化的大小随电磁驱动压力增加的越快. 当电磁驱动压力 $\Delta p = 0.02$ MPa 时, Δp_c 在 $k > 1$, $k = 1$, $k < 1$ 这 3 种结构情况下有限元/理论值变化大小分别为 0.0049/0.005, 0.0072/0.0074, 0.008/0.008 MPa.

综上所述, 在印刷过程中, 下层 PDMS 薄膜最大位移和印戳缺陷处的压强变化大小都随着施加的电磁驱动压力增大而增大, 随着上下薄膜边长比、厚度、弹性模量的增大而减少. 当施加相同的电磁驱动力时, 薄膜边长比、厚度、弹性模量越小的印戳结构, 下层 PDMS 薄膜的变形位移效果最好. 此时, 印戳缺陷处的压强增大量最大, 在印刷过程中效果最好.

2.2 上墨过程

上墨过程中, 在反向电磁场的作用下, 印戳上层的磁性薄膜向上运动, 带动下层薄膜向上凸起, 使印戳底部空腔缺陷处的体积变大、压强变小, 从而可以增大印戳和电子元件间的作用力. 与印刷过程

图 2 (网络版彩图) 印刷过程中下层薄膜变形的最大位移与电磁驱动压力的关系

Figure 2 (Color online) The relationship between maximum displacement of film deformation and electromagnetic driving pressure during printing. (a) The film thickness is different; (b) the side length ratio between the upper and lower films is different; (c) the elastic modulus is different

图 3 (网络版彩图) 边长比不同时, 印刷过程中印戳底部缺陷处的压强变化大小与电磁驱动力的关系

Figure 3 (Color online) Relationship between the pressure change of the bottom opening cavity and electromagnetic driving pressure during printing for different side length ratios

中的理论推导类似, 可以得到上墨过程中印戳缺陷处的压强变化大小 Δp_c 为

$$\Delta p_c = \frac{64w_{\text{bot}}^{\max}}{225h_c + 64w_{\text{bot}}^{\max}} p_{c0}. \quad (16)$$

图 4 (网络版彩图) 上墨过程中下层 PDMS 变形的最大位移与电磁驱动压力的关系

Figure 4 (Color online) Relationship between the maximum displacement of bottom film and electromagnetic driving pressure during pickup. (a) The film thickness is different; (b) the side length ratio between the upper and lower films is different; (c) the elastic modulus is different

下层 PDMS 薄膜变形的最大位移值 $w_{\text{bot}}^{\text{max}}$ 和电磁驱动力 Δp 的关系为

$$\Delta p = \frac{3hw_{\text{bot}}^{\text{max}}}{a_{\text{bot}}^2} \left[20.9(1 + \lambda k^6) \bar{E}_{\text{bot}} \frac{h^2}{a_{\text{bot}}^2} + 12.3(1 + \lambda k^{10}) \bar{E}_{\text{bot}} \frac{(w_{\text{bot}}^{\text{max}})^2}{a_{\text{bot}}^2} \right] + \frac{64w_{\text{bot}}^{\text{max}}}{225h_c + 64w_{\text{bot}}^{\text{max}}} p_{c0}. \quad (17)$$

式 (17) 给出了上墨过程中印戳底部薄膜的最大位移 $w_{\text{bot}}^{\text{max}}$ 与磁性薄膜在电磁场作用下产生的电磁驱动压力 Δp 之间的关系, 与上下层薄膜的弹性参数、边长比和厚度有关。

图 4 所示为上墨过程中下层 PDMS 薄膜的最大变形量 $w_{\text{bot}}^{\text{max}}$ 与电磁驱动压力 Δp 的关系, 下层薄膜的最大位移总是随着电磁驱动压力的增大而增大。在相同的电磁驱动力作用下, 薄膜厚度越小, 下层薄膜产生的最大位移越大; 薄膜边长比越小, 下层薄膜的最大位移越大; 弹性模量越小, 下层薄膜的最大位移越大。在上墨过程中, 下层薄膜向上的变形越大, 开口空腔处的体积增加就越大, 相应的压强减小就越大, 就越有利于上墨。从图 5 可以看出缺陷处压强变化的大小 Δp_c 随着电磁驱动压力增大而增大, 并且随着电磁驱动压力增大的速率逐渐减小; 边长比越小的印戳, 缺陷处压强变化的大小随电磁驱动压力增加的越快。在上墨过程中, 当施加相同的电磁驱动力时, 薄膜边长比、厚度、弹性模量越小的印戳结构, 下层薄膜的变形位移越大, 引起印戳底部缺陷处的压强减小量也越大大, 在上墨过程中效果最好。

图 5 (网络版彩图) 边长比不同时, 上墨过程中印戳底部缺陷处的压强变化大小与电磁驱动力的关系

Figure 5 (Color online) Relationship between the pressure change of the bottom opening cavity and electromagnetic driving pressure during pickup for different side length ratios

2.3 含四棱台空腔转印印戳的力学模型

式 (15) 和 (17) 分别描述了在上墨和印刷的过程中下层 PDMS 薄膜最大位移 $w_{\text{bot}}^{\text{max}}$ 与电磁驱动压力 Δp 的关系, 在引入一个因子 α 后, 两个式子可以统一为

$$\Delta p = \frac{3hw_{\text{bot}}^{\text{max}}}{a_{\text{bot}}^2} \left[20.9(1 + \lambda k^6) \bar{E}_{\text{bot}} \frac{h^2}{a_{\text{bot}}^2} + 12.3(1 + \lambda k^{10}) \bar{E}_{\text{bot}} \frac{(w_{\text{bot}}^{\text{max}})^2}{a_{\text{bot}}^2} \right] + \frac{64w_{\text{bot}}^{\text{max}}}{225h_c + \alpha 64w_{\text{bot}}^{\text{max}}} p_{c0}, \quad (18)$$

其中 $\alpha = 1$ 表示印刷过程, $\alpha = -1$ 表示上墨过程. 则在转印过程中印戳底部开口空腔处压强变化的大小可以写成

$$\Delta p_c = \frac{64w_{\text{bot}}^{\text{max}}}{225h_c + \alpha 64w_{\text{bot}}^{\text{max}}} p_{c0}. \quad (19)$$

最后可以得到转印中印戳底部开口空腔处的压强为

$$p_c = \left[1 + \frac{64\alpha w_{\text{bot}}^{\text{max}}}{225h_c + \alpha 64w_{\text{bot}}^{\text{max}}} \right] p_{c0}. \quad (20)$$

当 $E_{\text{bot}} = E_{\text{top}} = 1$ MPa, $\nu_{\text{bot}} = \nu_{\text{top}} = 0.45$, $a_{\text{bot}} = 12$ mm 时, 印戳空腔缺陷处的压强和电磁驱动力关系的理论结果和有限元结果如图 6 所示, 对于不同的印戳薄膜边长比, 理论结果和有限元结果基本一致. 在上墨中空腔缺陷处的压强随着电磁驱动压力增大而减小, 随着边长比的增大而增大; 而在印刷的过程中, 印戳空腔缺陷处的压强随着电磁驱动压力增大而增大, 随着边长比的增大而减小. 当电磁驱动压力为 0.02 MPa、薄膜边长比为 0.75, 1, 1.2 时, 空腔缺陷处的压力在印刷中分别增大到 0.110, 0.108, 0.105 MPa, 在上墨中分别减小到 0.0916, 0.0930, 0.0950 MPa, 此时空腔缺陷处的压力在整个转印过程中的变化分别为 0.0184, 0.015, 0.010 MPa, 分别为空腔初始压力的 18.4%, 15%, 10%. 在上墨过程中, 空腔缺陷处的压力越小效果越好; 印刷的过程中, 空腔缺陷处的压力越大效果越好. 因此, 本文中提出的印戳在边长比小于 1 的情况下转印效果最好, 即内含的密闭空腔以倒置的四棱台型为最好.

3 结论

本文提出了一种内含四棱台空腔结构的电磁辅助转印印戳. 在交变电磁场作用下, 印戳上部的磁性薄膜发生凹凸变形并通过空腔内封装的液体传递给底部的柔性薄膜, 从而改变印戳底部空腔缺陷处

图6 (网络版彩图) 薄膜边长比不同时, 转印中印戳缺陷处压强与电磁驱动压力的关系

Figure 6 (Color online) Relationship between the pressure of the bottom opening cavity and electromagnetic driving pressure during transfer printing for different side length ratios

的压力大小, 控制印戳和电子元件间的作用力. 采用能量法建立了印戳密闭空腔底部薄膜变形与施加的电磁驱动力之间的关系, 进而建立了转印中印戳底部开口空腔处的压强与印戳密闭空腔底部薄膜变形的定量关系. 理论模型得到了有限元结果的验证. 结果表明, 该印戳在转印过程中底部开口空腔缺陷处压力变化的大小随着电磁驱动压力的增大而增大, 而随着薄膜弹性模量、薄膜厚度、薄膜的边长比的增大而减小. 印戳薄膜边长比、厚度、弹性模量越小, 对转印越有利.

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Mechanical model of electromagnetic-assisted transfer-printing stamp containing a four-prism cavity

Qingmin YU*, Furong CHEN, Honglei ZHOU & Xudong YU

School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an 710129, China

* Corresponding author. E-mail: qingminyu@163.com

Abstract Transfer printing is a key step in the preparation of flexible and stretchable electronic devices, whereas the key to the transfer printing is to control the interfacial force between the stamp and device. In this study, a stamp containing a four-prism cavity for electromagnetic-assisted transfer printing is proposed and a mechanical model of the stamp is established. The magnetic film in the upper part of the stamp is deformed under the action of alternating electromagnetic field. Then, the deformation of upper film is transferred to the flexible film in the bottom part through the liquid in the four-prism cavity so as to change the pressure in the opening cavity at the bottom of the stamp and control the interfacial force between the stamp and device. Mechanical analysis shows that the value of the pressure change at the cavity opening at the bottom during transfer printing increases with increasing electromagnetic driving pressure, but decreases with increasing elastic modulus and thickness of the upper and lower films, as well as with increasing side-length ratio between the upper and lower films. The smaller the film side-length ratio, thickness, and modulus, the more favorable the transfer printing.

Keywords electromagnetic-assisted transfer printing, stamp, mechanical model, four prism cavity, finite element analysis

Qingmin YU was born in 1975. He received the B.E. degree in engineering mechanics in 1997, the M.E. degree in solid mechanics in 2005, and the Ph.D. degree in solid mechanics in 2007 from Northwestern Polytechnical University, Xi'an, China. From 1997 to 2001, he was an assistant lecturer at Cannon Command College. Since 2009, he has been an associate professor at the School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an, China. His research interests include the mechanics of stretchable and flexible electronics, meso-mechanics and damage mechanics, and mechanics of materials at high temperature.

engineering and Architecture, Northwestern Polytechnical University, Xi'an, China. His research interests include the mechanics of stretchable and flexible electronics, meso-mechanics and damage mechanics, and mechanics of materials at high temperature.

Furong CHEN was born in 1991. He received the B.S. degree in engineering mechanics in 2015 from Lanzhou University of Technology, Lanzhou. He is studying for the M.S. degree at Northwestern Polytechnical University, Xi'an. His research interest is stretchable and flexible electronics.

Honglei ZHOU was born in 1989. He received the B.E. degree in flight vehicle propulsion engineering in 2013 from Zhengzhou University of Aeronautics, China, and the M.S. degree in solid mechanics in 2016 from the School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, China. He is currently pursuing the Ph.D. degree in the School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, China. His main research

interests include the mechanics of stretchable and flexible electronics and the fatigue life and creep damage of materials and structures at high temperature.

Xudong YU was born in 1996. He received the B.E. degree in flight vehicle design and engineering in 2017 from Zhengzhou University of Aeronautics, China. He is currently a Master's degree candidate at the School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, China. His main research interest is the mechanics of stretchable and flexible electronics.