Analysis of stress concentration phenomenon in stretchable interconnects

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Abstract—Stretchable interconnects are essential structures in stretchable electronics. Typically, these structures are formed by metal conductors of different shapes on top of or encapsulated within a rubber material. Interfacial delamination during elongation is one of the major failures affecting the elasticity of interconnects. Stress concentration on substrate is the source of delamination. This study uses a numerical model of stretchable interconnects to analyze stress concentration phenomenon of typical structure shapes: the horseshoe, the zigzag, the U shape and the rectangle shape. The simulation is implemented by commercial finite element analysis software, ABAQUS. The simulation results demonstrate that stress concentrate area is larger at the edge of larger arc when out of plane deformation of the metal lines is small. However the geometrical configuration of the metal line shape has little effect on delamination. The phenomenon which found in this study cannot be ignored when designing metal line layouts.

***Keywords-** Stretchable electronics; stretchable interconnects; stress concentration; finite element analysis; ABAQUS*

I. INTRODUCTION

Stretchable electronics are the class of electronics that retain electric functionality under significant mechanical deformation. It has great potential in application of wearable electronics, flexible display, biomedical, healthcare and military [1], as shown in Fig .1. The elasticity of stretchable electronics derives from their deformable structures. One of the most favorable structures is the island-bridge structure, which uses stretchable interconnects, or bridges, that are lithographically etched into layouts of metal lines that connect rigid, functional islands on elastomeric substrates [2]. The metal line layouts can be configured in many different shapes that can accommodate of mechanical stress, while the elastomeric substrate guarantees that the metal line will revert to its original shape.

Several designs of metal lines have been reported in recent years, such as the U shape [3], the zigzag shape [4] and the horseshoe shape [5-7]. Self-similar shapes and fractal designs are also emerging, offering more multi-axial elasticity [8, 9]. These are structured by iteratively applying the U shape or horseshoe shape as a unit cell with different orientations, which enables them to tolerate multi-axial loads. However, designing metal line shapes that can endure considerable strain is still a crucial challenge for the functionality of stretchable interconnects.

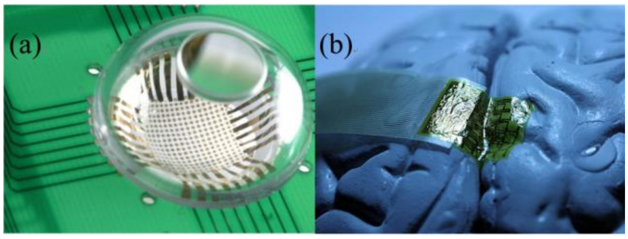

Figure 1. Applications in biology. (a). electronic eye [10], (b) stretchable circuit that can detect brain signal[11]

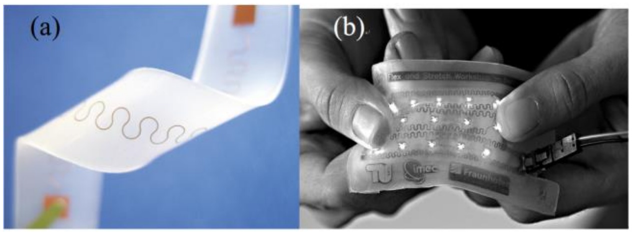

Figure 2. Types of strecthable interconnects. (a) horseshoe shape structure[7]. (b) U shape sturcture [6]

Another problem of stretchable interconnects is reliability. There are two major concerns for the structural reliability of stretchable interconnects. The first one is metal line fracture and the second is adhesive fracture (delamination) between the metal lines and the stretchable substrate at large strain [12-14]. Aiming at metal line fracture, lots of numerical studies have been made in focusing on the stress distribution on different types metal lines of stretchable interconnects [4-8]. In order to explain the stretch-induce delamination behavior in horseshoe shape structure, the finite element model was built in [12] where cohesive zone method (CZM) was applied to describe adhesive properties of the interface. However, there are convergent problems in CZM. The shear stress distribution on substrate was plot in [13] and [14], and stress concentration was observed on the substrate which indicates where delamination and material cratering may happen under tensile strains. Hence the stress distribution on substrate is a key indicator that can determine the delamination behavior of stretchable interconnects. Nevertheless, how stress distributed, how the geometrical design of the metal lines affect the stress distribution on substrate are still unclear and therefore requires more studies on this topic.

This paper presents a numerical analysis to investigate stress concentration phenomenon as it is affected by the geometrical configuration of the metal lines. First, three dimensional finite element analysis (FEA) models of the horseshoe, the zigzag, the U shape and the rectangle shape of copper lines in PDMS substrates were built to analyze stress on substrate. Then, the impact of geometrical configurations on stress distribution in elastomeric substrates was investigated to further the understanding of stress concentration phenomenon.

II. MODELING

In this study, FEA was utilized to simulate stretchable interconnects under tensile stress. Fig .3 illustrates the zigzag shape, horseshoe shape U shape and rectangle shape formed by copper lines configured in PDMS substrates. The thickness of the copper lines and the substrate were 18 μm and 0.5 mm, respectively. The width of metal line was 0.1mm. Each of the structures contained two unit cells. The period of each metal lines are the same. Uniaxial elongation was applied to the substrate at both ends of the structures. 60% elongation was applied to all structures, corresponding to experimental conditions in [12].

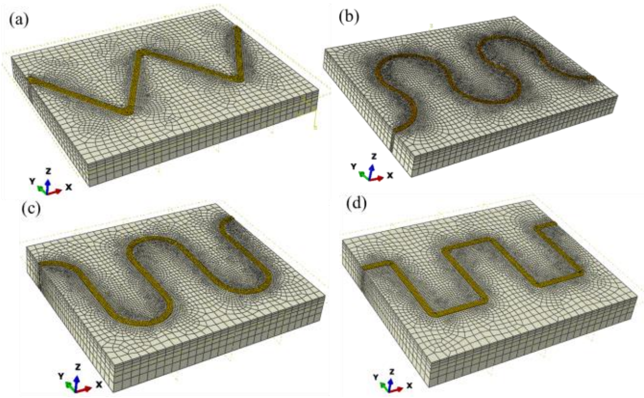

Figure 3. Finite element modeling of stretchable electronics. (a) Zigzag shape sturcture, (b) horseshoe shape strucutre, (c) U shape structure, (d) rectangle shape.

The mechanical behavior of the PDMS rubber substrate is described by an incompressible neo-Hookean hyperelastic model [15] with C10 = 0.165 Mpa and D1 = 0. This hyperelastic model corresponds well with experimental data up to strains of 150% [16].

The metal used in this study was copper and a nonlinear elasto-plastic model was employed with Young's module, E = 85 Gpa, the yielding point at y = 200 Mpa [17]. The elasto-plastic curve of the metal is demonstrated in Fig . 4.

The commercial FEA software, ABAQUS, was used to simulate the deformation process and calculate strain and stress on the copper lines and substrate. Mesh details are demonstrated in Fig .3. Hybrid elements were selected to describe the incompressible behavior of the PDMS substrate.

A parametric modeling method based on python scripts for ABAQUS provided efficiency by facilitating the definition of new structures with changes to only a few essential parameters. Mesh convergence were checked.

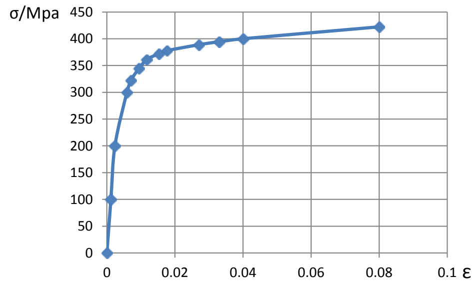

Figure 4. Elasto-plastic curve of the copper foil

III. RESULTS AND DISCUSSION

A. *Effects of metal line layouts on stress concentration phenomenon*

Fig .5 plots the stress concentration in deformed horseshoe shape, zigzag shape, rectangle shape and U shape structures under elongation of up to 60% respectively. In horseshoe shape and zigzag shape structures, stress concentration is observed at the area fit well with the region where fibrillation takes place comparing the experiment results in [12]. Even though there are no comparisons, it can be believed that the simulation results in Fig .5(c) and (d) are convincible. Under the same elongation, the stress concentration region in the substrate of the horseshoe structure is the largest, U shape the second, rectangle shape the third and zigzag shape has minimum area.

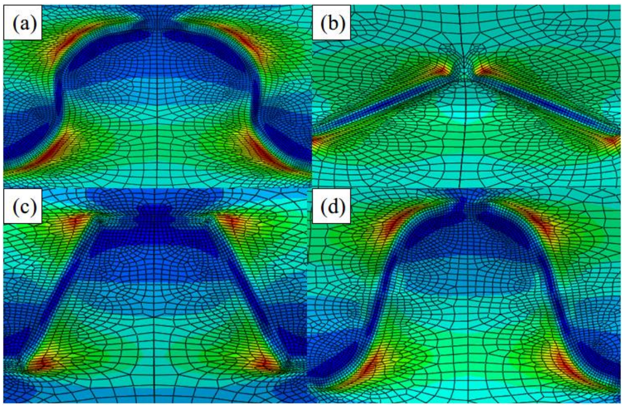

Figure 5. Von Mises stress on substrate at 60% tensile strain. (a) horseshoe shape strucutre, (b) Zigzag shape sturcture, (c) rectangle shape, (d) U shape structure.

In Fig .5 (a), (c), (d), in-plane shear stress or tensile stress on the surface of the substrate is domain stress. This is because out of plane deformations of these structures are relatively small which lead to larger stress concentrate area at the edge of larger arc according to the figures. In Fig .4 (b), the zigzag shape structure, normal stress dominates the stress concentration area. Because two sides of the zigzag crest are twisting when tensile strain is applied. Thus the stress concentration phenomenon can be explained by deformation behavior of the metal lines.

B. *Effects of geometrical parameters on stress concentration on substrate*

To identify the effect of geometrical design on the delamination behavior of stretchable interconnects under tensile stress, the horseshoe structure was chosen for the simulation. The horseshoe shape can be defined by two parameters: scale factor (R/W) and angles (α), shown in Fig .6, where R represents the curvature radius and W represents the width of the metal line.

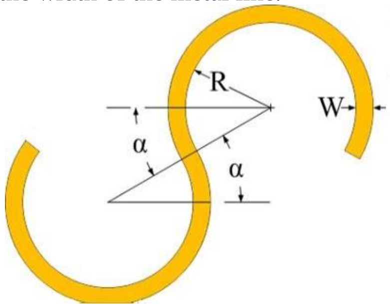

Figure 6. Parameters of the horseshoe shape structure.

Defining scale factor R/W means that the stress and strain induced in the metal are constant if the ratio is kept constant, independent of the amplitude of the horseshoe design [6]. However, holding R constant, but varying W results in variable R/W.

TABLE I. HORSESHOE SHAPE PARAMETER VALUES

Parameter	Values			
Radius R (mm)	0.8	0.8	0.8	0.8
Width W (mm)	0.08	0.1	0.12	0.14
Angle α (°)	30	35	40	45

The simulation results are plotted in Fig .7. Due to the length of the paper, only two stress cloud charts were illustrated. It is obvious that stress concentration still locate at the two side of the horseshoe crest.

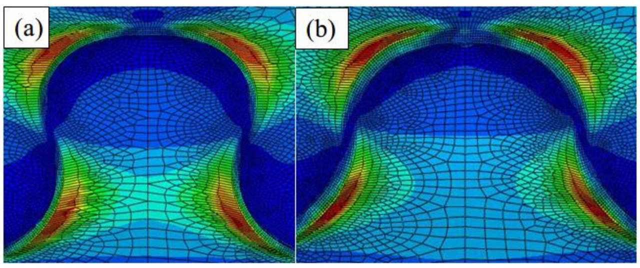

Figure 7. Stress distribution on horseshoe shape with different parameters. (a) W=0.08mm, α=45 °. (b) W=0.14mm, α=30 °

Effects of parameters on the stress value with horseshoe structure are demonstrated in Fig .8. There are 12 sets of data curves in the chart divided into three groups. Each group represents all 16 horseshoe shape structures under the elongations of 60%, 40%, and 20%, respectively. Fig .8 shows that W had little effect on the stress at lesser elongations (20% and 40%), and stress increased slowly as α increased. However, Fig .8 shows more variation in trends at 60% elongation, a phenomenon attributed to simulation inaccuracy. The inaccuracy has two primary sources. First, in nonlinear large deformation analysis, elements may distort excessively at large strains, which will result in inaccurate results on those element nodes. Second, the neo-Hookean hyperelastic model remains accurate for strains up to 150%, but the strain on some element nodes exceeded this limit in this study. The deference between mesh size of the substrate will also lead to the inaccuracy. Despite the inaccuracy of the simulation model when describing large strain, as discussed in Section 3.1, the general trends in stress variation at low elongations are convincing, indicating a limited influence of these parameters on the delamination of stretchable interconnects.

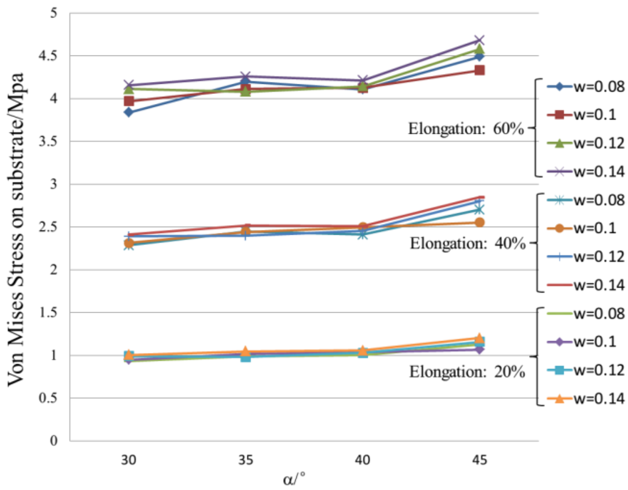

Figure 8. Effects of parameters on the stress on the substrate with horseshoe structure

IV. CONCLUSION

In summary, this study presents numerical analysis of simulations of stretch-induced delamination behavior in different geometrical configurations of metal lines in stretchable interconnects. First, a finite element model was established. The effects of metal line layouts on stress concentration phenomenon were discussed. The results show that the stress concentration phenomenon can be explained by deformation behavior of the metal lines. Finally, the effects of geometrical parameters on stress distribution on the substrate were discussed. These results indicate that the geometrical parameters of a metal line have slight effect on the delamination of the structure. In the future, this numerical model will be modified to attain greater accuracy at larger elongations, which will allow us to predict delamination behavior and improve the reliability of stretchable interconnects.

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