Mechanical Performance Analysis and Optimization of Serpentine Wire Structures in Flexible Electronic Devices

Tianqi Dong *
College of Post and Telecommunication, Wuhan Institute of Technology, Wuhan, China, 430073
* Corresponding Author Email: 13593780703@163.com

Abstract. Aiming at the fatigue failure of serpentine wire in flexible electronic devices under repeated bending, stretching, and other large deformation scenarios, this paper takes the full-fit serpentine interconnect conductor as the research object, and constructs a three-dimensional model of multilayered heterostructure composed of conductor and substrate based on ABAQUS finite element platform, and systematically researches the influence of the material parameters of the conductor and the substrate on the elongation rate of the serpentine structure, such as elasticity modulus. The material parameters of wire and substrate, including modulus of elasticity, Poisson's ratio, as well as geometric parameters of wire, such as line width, length of the straight-line section, bending radius and their combinations, affect the ductility of the serpentine structure. The experimental results show that the modulus of elasticity of the substrate is positively correlated with the ductility, the increase of the line width of the wire significantly reduces the ductility, the increase of the bending radius effectively improves the ductility, and the influence of the length of the straight-line segment on the ductility is nonlinear; orthogonal tests further reveal the coupling between the geometrical parameters of the wire. The research results provide a theoretical basis for the design of flexure-resistant structures for flexible electronic devices.

Keywords: Flexible electronic devices, Serpentine wire structure, Elongation, Finite element analysis, Mechanical properties.

1. Introduction

With the rapid development of wearable devices, implantable medical devices, soft robots, and other technologies, the application field of flexible electronic devices is expanding and has gained a variety of different functions and forms of applications [1]. It can be used to manufacture wearable solar photovoltaic panels, body surface health monitoring instruments, electronic eye cameras, electronic skin, smart electronic surgical tools, and many other devices that cannot be realized by traditional circuit preparation techniques [2]. However, in practice, these flexible devices often need to withstand repeated bending, stretching, and other complex large deformation conditions, resulting in the fatigue failure of the conductor, which has become a key issue that restricts the reliability of the system. Therefore, the mechanical properties of conductors face higher requirements and must have high ductility, excellent fatigue resistance, and good adaptability to complex deformation [3]. Conventional linear wires are prone to metal fracture or interface delamination under repeated deformation due to the stress concentration effect, which severely limits the reliability and service life of flexible electronic devices. In contrast, the serpentine structure has been widely used in flexible electronic devices by virtue of its excellent ductility, low tensile and bending stiffness, and other characteristics [4-5]. The study of the mechanical behavior of the serpentine structure can help to improve the understanding of its mechanical properties, which is of great significance for its further application in flexible electronics to bring more properties that are difficult to achieve in conventional electronics.

To ensure that flexible electronic devices maintain full functionality in complex external environments, it is essential to address the contradiction between the poor deformability of conductor materials and the high demands for extensibility and flexibility of the entire device. To enhance the elongation rate of flexible interconnect wires, many researchers have conducted design studies from two perspectives: the substrate and the serpentine wire. Wang [6] investigated the influence of three geometric parameters (length,line width, and thickness of the flexible substrate) on the elongation rate of serpentine wires using numerical simulation, finding that substrate length had minimal impact on extendibility, while increasing substrate width and thickness reduced system deformation and increased strain in the metal wire. Huang [7] explored the effects of serpentine wire width and long-pitch ratio on extendibility via numerical simulation. Li et al. [8] employed numerical simulation to study the influence of geometric parameters (substrate thickness, wire thickness, wire width) on elastic extendibility under pre-strained substrates. Furthermore, Liu [9] established a theoretical model for non-cracking serpentine wires, combined with finite element analysis, to investigate the effects of geometric parameters (straight segment length, arc radius) on extendibility. Yang [10] normalized three geometric parameters (width, arc angle, straight segment length), combined plane strain elasticity theory and bending beam theory, derived an analytical solution for the extendibility and equivalent stiffness of serpentine structures under small deformations, validated the model using finite element simulation and experiments, and ultimately achieved geometric optimization of isolated serpentine structures under practical constraints. Fan [11] addressed the limitation of traditional linear models in accurately predicting the performance of large-deformation serpentine interconnects by developing a nonlinear analytical model based on finite deformation theory, revealing that linear models overestimate extendibility and providing a simplified nonlinear model to offer high-precision theoretical references for the design of serpentine interconnects in stretchable electronics. While the above studies on the influence of geometric parameters of serpentine wires or substrates on the extendibility of flexible interconnects have provided key guidance for improving the performance of flexible electronic devices, most existing research focuses on the effect of individual geometric parameters on the extendibility of serpentine wires. However, the extendibility of serpentine wires is not only related to changes in individual factors but also to interactions between factors.

Based on this, this paper proposes a multi-parameter analysis method based on parametric modeling, taking fully bonded serpentine interconnect conductors as the research object, and constructing a three-dimensional heterogeneous structural model integrating wires and substrates. Through systematic research combining single-factor and orthogonal experiments, the influence laws of material parameters (elastic modulus, Poisson's ratio) and geometric parameters (line width, length of straight-line segment, bending radius) as well as their interaction effects on extendibility are revealed. On this basis, structural optimization strategies are proposed to optimize the comprehensive mechanical properties of serpentine wires. The research results provide theoretical support for the anti-bending structural design of flexible electronic devices, which is of significant engineering value for enhancing their service life and reliability.

2. Material model and property settings

2.1. Serpentine wire model

The research subject of this paper is a rectangular planar coil structure wound with a serpentine conductor, whose geometric features form a quasi-sinusoidal curve morphology composed of periodically alternating arc segments and straight segments. The key morphological parameters include four critical dimensions: straight segment length L, bending segment curvature radius R, conductor width W, and serpentine unit repetition cycle number N. As shown in Fig. 1, based on the ABAQUS finite element analysis platform, a three-dimensional stacked coil structure model was constructed using the shell element modeling function, enabling coupled geometric-mechanical analysis of the multi-layer coil.

Figure 1. Schematic diagram of the serpentine wire structure

The bonding constraints between the conductor and substrate must ensure mesh compatibility, proper selection of master and slave surfaces, and parameter adaptability. Through refined meshing, material property matching, and nonlinear settings under dynamic loading, the cohesive behavior of the wire-substrate interface can be effectively simulated to avoid simulation failure. In finite element analysis, a tie constraint is employed to simulate the fully bonded connection between the conductor and substrate, enforcing continuous displacement of contact surface nodes to eliminate relative sliding, separation, or penetration. The substrate is designated as the master surface, while the wire contact surface is set as the slave surface, excluding shell element thickness. Node positions are matched by setting positional tolerances, and initial overlaps are removed using the "Adjust Only to Remove Overlap" function. When there is a significant difference in material parameters (modulus of elasticity, Poisson’s ratio) between the substrate and conductor, enhanced mesh refinement and material property matching are required to mitigate stress discontinuities at the interface. The bonding constraint settings for the conductor and substrate are illustrated in Fig. 2.

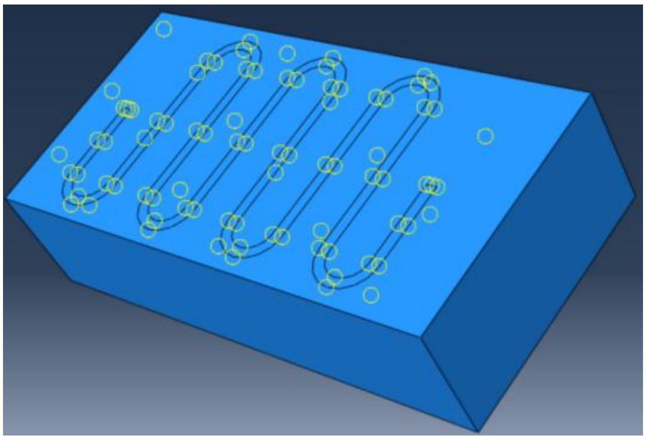

Figure 2. Conductor and substrate constraint settings

2.2. Material model and property settings

As shown in Fig. 3, the coil adopts a multilayer heterogeneous composite structure design, and the substrate layer is made of high-performance platinum-cured silicone Dragon Skin, which has a Young's modulus of 0.5 MPa and a Poisson's ratio of 0.49, providing flexible mechanical support for the system. The conductive layer consists of three layers of functional film: the upper and lower layers are made of polyimide, whose Young's modulus is 2500 MPa, Poisson's ratio is 0.27, as the upper layer of the insulation layer can effectively block the environment of oxidation and moisture erosion and provide electrical insulation performance, as the lower layer of the flexible substrate with the substrate layer to maintain the overall structure of the flexible encapsulation of the metal layer, the thickness of 0.015mm. The intermediate conductive layer Highly ductile metal materials are selected, synthetic copper with Young's modulus of 110 GPa and Poisson's ratio of 0.33, and synthetic aluminium with Young's modulus of 68 GPa and Poisson's ratio of 0.33, with a thickness of 0.002 mm. The material parameters of each layer are set as shown in Table 1.

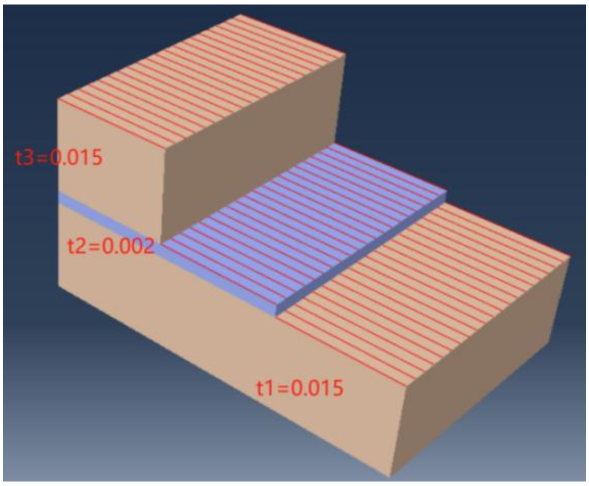

Figure 3. Schematic diagram of layer stacking

Table 1. Material parameter settings for the three layers of the serpentine wire

Material	Modulus of elasticity	Poisson's ratio
Substrate material	0.5 MPa	0.49
Conductor upper and lower material	2500 MPa	0.27
Conductor metal layer material Cu	110 GPa	0.33
Conductor metal layer material Al	68 GPa	0.33

As shown in Fig. 4, the mesh generation employs the medial axis algorithm with a global size of 1.0 and a curvature deviation factor of 0.1 to produce quadrilateral elements, with the hourglass control enhancement function activated to balance mesh density and computational efficiency. Critical validation of the comprehensive effects of boundary conditions, constraint settings, and mesh parameters on numerical convergence and simulation accuracy is necessary to prevent computational overload or abnormal termination. As illustrated in Fig. 5, displacement boundary conditions (U_1=5, U_2=−5, U_3=0) are applied to both ends of the substrate in the finite element simulation to replicate multi-directional loading scenarios, while a tie constraint is implemented to eliminate interface slippage between the metal layer and the substrate. The static general algorithm is selected for the analysis step, configured with an initial increment of 0.001, a maximum increment of 0.1, and a minimum increment of 1E−50, and the adaptive stability criterion is applied to control the maximum stable strain energy ratio at 0.05.

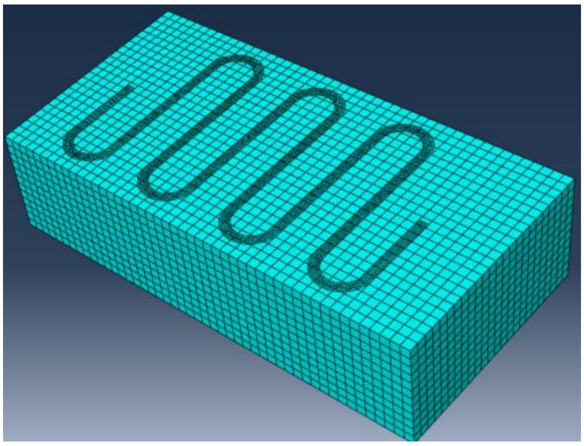

Figure 4. Grid module display

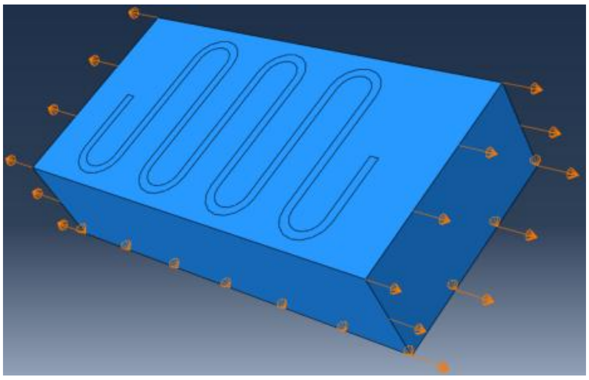

Figure 5. Boundary condition setting

3. Result Analysis

3.1. Effect of the Geometric Parameters of the Serpentine Wire Itself on the Elongation Rate

The tensile performance of the serpentine wire is co-regulated by its wire width, bending radius, and straight segment length. These three parameters collectively influence the wire's elongation rate by adjusting the local stress distribution and strain dispersion efficiency. As shown in Fig. 6, under the conditions of a copper (Cu) wire with a Young's modulus of 110 GPa, a Poisson's ratio of 0.33, a substrate modulus of 166 MPa, and a boundary strain of 10%, the stress-strain curve and parametric line graph based on ABAQUS indicate that the geometric parameters significantly affect the variation in elongation rate by altering the wire's cross-sectional area, the stress concentration level in the bending region, and the strain path distribution. Among these, the wire width exerts the most pronounced impact on the elongation rate.

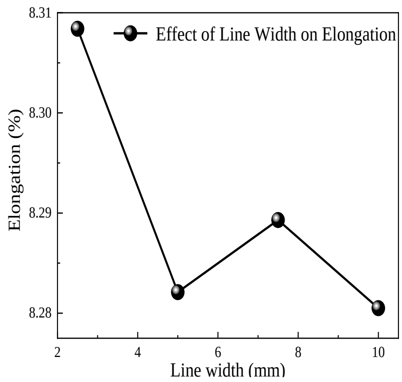

Figure 6 (a). Line width

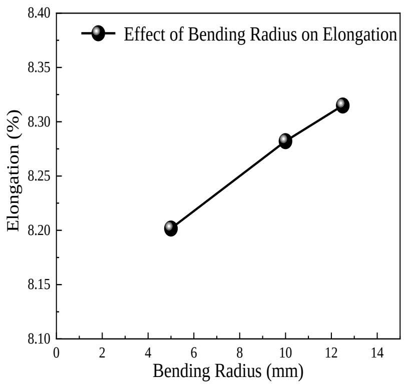

Figure 6 (b). Bending radius

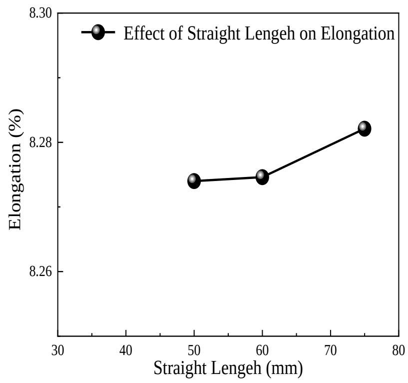

Figure 6 (c). length of straight-line segment

Under the boundary conditions $U_1=5$, $U_2=-5$, $U_3=0$, as shown in Fig. 6(a), the stress concentration effect indicates that a reduction in wire width significantly increases local stress, particularly prone to inducing crack initiation in the transition zone between the bending segment and the straight segment. An excessively small wire width may cause the current density to exceed the material threshold. As shown in Fig. 6(b), the bending segment radius determines the local curvature—reducing the radius increases stress, which can easily lead to material yielding or fracture. Additionally, under cyclic loading, the fatigue crack propagation rate in regions with small radii accelerates notably. As shown in Fig. 6(c), during tensile deformation, the straight segment primarily bears axial loads. Its length influences the strain distribution of the entire structure: a short straight segment concentrates strain in the bending segment, potentially leading to premature failure; a long straight segment shares more axial strain but may reduce geometric ductility.

3.2. Effect of the Flexible Substrate on the Elongation Rate of the Serpentine Wire

The substrate modulus influences the elongation rate by regulating stress distribution and interfacial behavior. Under the conditions of a straight segment length of 75 mm, a wire width of 5 mm, a bending segment radius of 10 mm (geometric parameters), a metal type of Cu, and a Poisson's ratio of 0.49, three sets of parameters (166 MPa, 1 MPa, 0.5 MPa) are set to analyze the influence of the substrate's elastic modulus on the elongation rate of the serpentine wire. The parameter settings are shown in Table 2.

Table 2. Substrate modulus parameter settings

No.	Substrate modulus (MPa)	Tensile rate (%)
1	166	8.2821
2	1	7.893
3	0.5	7.6922

The high-modulus substrate (166 MPa hard material) enhances the substrate stiffness through the hourglass effect, achieves efficient stress transfer and resists deformation with the metal layer (Cu, 110 GPa), effectively relieves the stress concentration, and obtains a small increase in the tensile rate; whereas, the low-modulus substrate (e.g., 0.5 MPa) is too soft and leads to an uneven distribution of stress, and the substrate is unable to bear the function of load transfer, and the metal layer induces the premature fracture by the concentration of the local strains. Premature fracture and the tensile rate are significantly reduced. The modulus matching between the substrate and the metal is the core element to control the tensile properties. A high-modulus substrate optimizes stress diffusion, but excessive rigidity may lead to the risk of brittle damage; a low-modulus substrate limits ductility due to interfacial instability. In practical engineering, a synergistic optimization of mechanical properties and functional reliability should be achieved through modulus matching design combined with interfacial toughening.

The modulus of elasticity of the flexible substrate dominates the strain field distribution of the metal layer through the interfacial stress transfer and deformation coordination characteristics. Although the high deformation coordination ability of the low modulus substrate can realize the cooperative deformation between the substrate and the metal layer and reduce the interfacial shear stress, it is easy to trigger the serpentine wave flexural instability; the rigidity constraint of the high modulus substrate reduces the local stress peaks through the strain dispersion effect of the serpentine geometry, but the difference of the modulus is too large and results in the concentration of the interfacial shear stress. As shown in Fig. 7, insufficient substrate stiffness triggers metal layer buckling folds, while too high modulus leads to interface delamination failure.

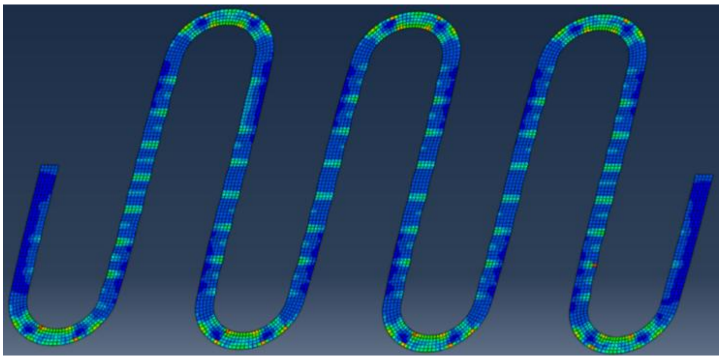

Figure 7. Schematic diagram of localized folding of the serpentine wire

3.3. Multi-factor Experiments

3.3.1. Multi-factor Experiment on the Geometric Parameters of the Serpentine Wire Itself

The multi-factor coupling mechanism of the geometric parameters of the serpentine wire has a decisive effect on the tensile performance, in which the synergistic relationship between the line width, bending radius, and linear segment length determines the strain energy distribution and failure mode. In this paper, the coupling effect of this geometric parameter is investigated through an orthogonal experimental design system. Under the elastic modulus of serpentine wire of 1 MPa and Poisson's ratio of 0.1, 15 groups of parameter combinations are set up (line width of 2.5-10 mm, bending radius of 5-12.5 mm, straight line segment length of 50-75 mm), to analyze the effect of the interaction between the geometric parameters of the serpentine wire itself on the plastic deformation capability of the metal layer. The parameter settings are shown in Table 3.

Table 3. Multi-factor experimental design of serpentine wire geometric parameters

No.	Wire width (mm)	Radius (mm)	Length of straight section (mm)	Tensile rate (%)
1	2.5	10	60	4.0632
2	10	10	60	3.9970
3	5	5	60	3.7474
4	5	12.5	60	4.0409
5	5	10	50	3.9316
6	5	10	75	3.9228
7	2.5	5	50	3.7589
8	2.5	12.5	75	3.9209
9	10	5	75	3.526
10	10	12.5	50	3.8468
11	5	10	60	3.9294
12	2.5	10	75	3.898
13	10	10	50	3.9926
14	5	5	75	3.5682
15	5	12.5	50	3.8717

As shown in Table 3, the tensile properties of serpentine wires are affected by the nonlinear coupling of line width, bending radius, and straight segment length. Small wire width optimizes stress distribution by reducing the cross-sectional moment of inertia but needs to be paired with a large bending radius to suppress local stress concentration. For example, the serial number 1 experiment (W=2.5 mm, R=10 mm, L=60 mm) achieves a maximum tensile rate of 4.0632% with the help of parametric synergy. A medium bending radius balances the stress concentration with strain dispersion, while too large a radius needs to be combined with long straight segments to avoid localized stretching. As in the serial number 8 experiment (W=10 mm, R=12.5 mm, L=75 mm), a high tensile rate (3.9209%) is maintained by parameter matching. There is an optimal interval (60-75 mm) for the length of the straight section, too short is prone to fatigue fracture of the bending section (e.g., Experiment 5 with L=50 mm yields an elongation rate of 3.9316%), and too long reduces the geometric ductility (e.g., Experiment 14 with L=75 mm yields an elongation rate of 3.5682%). The parameter interactions indicate that the combination of small wire width and large radius significantly enhances the tensile performance, providing a key reference for the design of wire ductility improvement.

The tensile performance of the serpentine wire depends on the yield strength and plastic deformation capacity of the metal material. High-yield-strength materials delay plastic deformation, maintaining structural stability under low strain but prone to stress accumulation in the bending segment, leading to local fracture and limiting overall elongation. Low-yield-strength materials disperse stress through plastic flow, adapting to the geometric expansion of the serpentine structure, but premature yielding may cause structural relaxation, necessitating geometric parameter optimization to balance ductility and stiffness.

3.3.2. Multi-factor Experiment on the Material Parameters of the Serpentine Wire Itself

The synergistic effect of base modulus and metal modulus affects the tensile rate by regulating the stress distribution and interface behavior. High base modulus inhibits metal deformation but improves uniformity, while low base modulus exacerbates modulus mismatch leading to brittle failure. The coupling effect of this material parameter is explored through an orthogonal design of experiments system to analyze the effect of synergism between material parameters on the plastic deformation capacity of the metal layer of the serpentine wire itself under the length of straight-line segment of 75 mm, line width of 5 mm and a bending section with a radius of 10 mm. Parameter settings are shown in Table 4.

Table 4. Multi-factor experimental design of material parameters of serpentine wire

No.	Substrate modulus (MPa)	Metal modulus (GPa)	Tensile ratio (%)
1	166	110	8.2821
2	1	110	7.893
3	0.5	110	7.6922
4	166	200	8.2615
5	1	200	3.9237
6	0.5	200	3.9252
7	166	68	8.2938
8	1	68	3.9329
9	0.5	68	3.9228

As shown in Table 4, the effect of the substrate modulus on the tensile rate of the serpentine wire presents a significant difference. When the base modulus is fixed at 166 MPa, the metal modulus increases from 68 GPa to 200 GPa, and the tensile rate only decreases by 0.4%, indicating that the high-stiffness base dominates the system deformation, and the plastic deformation of the metal layer has a limited effect on the overall performance. However, when the modulus of the substrate decreases to 1 MPa or 0.5 MPa, the same increase in metal modulus leads to a decrease in the tensile rate of more than 50%, which is due to the fact that the flexible substrate is unable to disperse the stress, and the high modulus of the metal exacerbates the concentration of local stress, increasing the risk of fracture. Comparatively, it is found that when the metal modulus is fixed at 200 GPa, the substrate modulus decreases from 166 MPa to 0.5 MPa, and the tensile rate decreases from 8.26% to 3.92%, which is mainly attributed to the concentration of shear stresses induced by the increased difference in interfacial stiffness. The experimental results show that the substrate modulus is the key factor to control the tensile rate. The high base modulus (166 MPa) stabilizes the tensile rate by enhancing the system stiffness, while the low base modulus (0.5 MPa) significantly reduces the ductility due to the premature failure of the metal layer caused by the interfacial mismatch.

4. Summary

In this paper, we propose a multi-case analysis method based on parametric modeling for the fatigue failure of serpentine wires in flexible electronic devices under large deformation. ABAQUS is used to construct a multilayer heterogeneous structure model of wire-substrate, and the effects of material parameters (modulus of elasticity, Poisson's ratio) and geometrical parameters (line width, length of straight-line segment, bending radius) and their interactions on the ductility of the wire are investigated through a one-way and orthogonal test system. The study shows that the modulus of elasticity of the substrate is positively correlated with the ductility of the conductor, but too high is prone to cause brittle breakage; reducing the line width and increasing the bending radius can improve the ductility, and the synergistic effect of the two is significant. The orthogonal test reveals the nonlinear coupling law between the parameters, pointing out that the combination of the small wire width and the large bending radius is an effective strategy to optimize ductility performance. The research results provide a theoretical basis for the design of bend-resistant serpentine interconnect structures for flexible electronic devices, which is of guiding significance for improving their service life and reliability.

References

[1] Peng YX, Chen XY, Zhang YK. Current status, challenges, and innovative strategies of flexible electronic materials and devices in field of wearable sensing [J]. Journal of Materials Engineering, 2024, 52 (8): 42 - 58.

[2] Hong S, Lee S, Kim D H, Materials and Design Strategies of Stretchable Electrodes for Electronic Skin and its Applications [J]. Proceedings of the IEEE. 2019: 2185 - 2197.

[3] Lim H R, Kim H S, Qazi R, et al. Advanced soft materials, sensor integrations, and applications of wearable flexible hybrid electronics in healthcare, energy, and environment [J]. Advanced Materials, 2020, 32 (15): 1901924.

[4] Li R, Li M, Su Y, et al. An analytical mechanic's model for the island-bridge structure of stretchable electronics[J]. Soft Matter, 2013, 9 (35): 8476 - 8482.

[5] Chen ZR, Huang X. Investigation of the optimization approach to improve flexibility of flexible hybrid circuit and its application [J]. Journal of Electronic Measurement and Instrumentation, 2023, 37 (10): 74 - 79.

[6] Wang XL, Li H, Wang GQ. Effect of the geometric parameters of elastomer substrates on the flexibility of stretch-able electronics[J]. Chinese Journal of Engineering, 2015, 37 (S1): 24 - 28.

[7] Huang T, Dong WT, Xiao L, et al. Stretchability of U-patterned interconnect on elastic substrate [J]. Modern Manufacturing Engineering, 2017, (04): 17 - 21+49.

[8] Li XT, Tong HY, Zhao Y, et al. The quasi-static response of granular materials toa concentrated loading [J]. Chinese Journal of Applied Mechanics, 2015, 32 (02): 251 - 255+353.

[9] Liu H, Xue RY, Hu JQ, et al. A systematic study on the mechanical and electrical behaviors of the nonbuckling interconnect design of stretchable electronics [J]. Science China Physics, Mechanics & Astronomy, 2018, 61: 1 - 9.

[10] Yang S, Qiao S, Lu N. Elasticity Solutions to Nonbuckling Serpentine Ribbons [J]. Journal of Applied Mechanics-Transactions of the ASME. 2016. 84 (2): 21004.

[11] Fan Z, Zhang Y, Ma Q, et al. A finite deformation model of planar serpentine interconnects for stretchable electronics [J]. International Journal of Solids and Structures. 2016. 91: 46 - 54.