Simulation Study on the Mechanical Behavior of Silver Wires Composed of Multi-Scale Nanoparticles

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Abstract

As an important component of flexible electronic devices, flexible interconnect wires printed with nanoparticle-based conductive silver ink require investigation into how their microstructure affects mechanical behavior, which is of great significance for improving the service reliability of flexible electronic products. A random circular packing algorithm was used to establish a two-dimensional finite element model of the microstructure of nanoparticle-based silver wires, and a cohesive zone model was adopted to describe the bonding force between particles. The effects of microstructures composed of different average particle sizes (30-80 nm), standard deviations (0-45 nm), and porosities on the mechanical properties of silver wires during tensile deformation were investigated. The results show that the standard deviation of particle size is the main factor affecting the porosity of silver wires, and that the mechanical properties of nanoparticle silver wires are significantly improved as their microscopic porosity decreases. The effects of the average particle size and proportion of small particles on the mechanical behavior of silver wires with particle sizes following a bimodal normal distribution were further analyzed. The results indicate that, owing to their smaller average particle size, small particles can be better embedded in the gaps among packed large particles, thereby reducing the porosity of silver wires and significantly improving their mechanical properties.

Full Text

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Abstract: Flexible interconnecting wires printed with nanoparticle conductive silver ink, serving as important components of flexible electronic devices, are of great significance for improving the service reliability of flexible electronic products by studying how their microstructure affects their mechanical behavior. A two-dimensional finite element model of the microstructure of nanoparticle silver wires was established using a random circular-packing algorithm, and the bonding force between particles was described using a cohesive-zone model. The effects of microstructures composed of different average particle sizes (30–80 nm), standard deviations (0–45 nm), and porosities on the mechanical properties of silver wires during stretching were investigated. The results show that the

standard deviation of particle size is the main factor influencing the porosity of silver wires, and the mechanical properties of nanoparticle silver wires improve significantly as their microscopic porosity decreases. The effects of the average particle size and the proportion of small particles on the mechanical behavior of silver wires in which particle sizes follow a bimodal normal distribution were further analyzed. The results show that, because small particles have smaller average particle sizes, they can be more readily embedded into the gaps of large-particle stacks, thereby reducing the porosity of silver wires and significantly improving their mechanical properties.

Keywords: printed silver wire; nanoparticles; cohesive-zone model; porosity; mechanical behavior

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Simulation on mechanical behavior of silver wire composed by multi-scale nanoparticles

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Abstract: The flexible interconnecting wires printed by nanoparticle conductive silver ink are an important component of flexible electronic devices. Studying the influence of their microstructure on mechanical behavior is of great significance for improving the service reliability of flexible electronic products. The two-dimensional finite element model of the microstructure of nanoparticle silver wire was carried out based on the random circular stacking algorithm, and the bonding force between the particles was modeled by cohesive zone model. The effect of microstructure composed of particles with different average particle sizes (30–80 nm), standard deviations (0–45 nm), and porosity on the mechanical properties of silver wires

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during stretching was studied. The results indicate that the standard deviation of particle size is the main factor affecting the porosity of silver wires, and the mechanical properties of nanoparticle silver wires significantly improve with the decrease of their micro porosity. In addition, the wire composed of particles with bimodal normal distribution was modeled, and the impact of the average particle size and proportion of the small particles on the mechanical behavior of silver wires were analyzed. The results show that particles with smaller average size can be well embedded in the gaps of large particles, which can lead to the reducing of porosity of the silver wires, and significantly improving their mechanical properties.

Key words: printed silver wire; nanoparticles; cohesive zone model; porosity; mechanical behavior

Flexible electronics, as an emerging microelectronic technology, can maintain the original functions of electronic devices under various complex deformation conditions such as bending and stretching[^1-4]. In recent years, with the development and application of new materials and new processes, related flexible electronic products, such as flexible displays[^5-8], flexible sensors[^9-12], and flexible solar cells[^13-16], have begun to emerge and enter people' s lives. However, before large-scale commercialization, the long-term service reliability of flexible electronic products is a key problem that must be solved. As a key component, flexible silver conductors are a crucial link determining the performance of flexible electronic products.

Direct-writing printing technology based on nanoparticle conductive silver ink is an important method for preparing flexible silver conductors. Nanoparticle conductive silver ink is composed of silver nanoparticles, solvents (water or alcohols), surfactants, dispersion stabilizers, and other additives mixed in certain proportions[^17]. A conductive pattern is obtained after printing and sintering. Studies have shown that the content of silver nanoparticles is an important factor determining the conductivity of printed patterns; the higher the silver content, the better the conductivity[^18]. In addition, the particle-size distribution of nanoparticles in silver ink is also an important factor affecting the performance of printed silver conductors. Liu et al.[^19] mixed two types of nanoparticles, 10 nm and 50 nm, in different proportions to prepare silver ink; the results showed that when the mass ratio of the two was 2:1, the conductivity of the printed silver conductor was optimal. Ding et al.[^20] used nanoparticle

Fig. 1 Physical image of the micro morphology of silver nanoparticle wires

Figure 1: Fig. 1 Physical image of the micro morphology of silver nanoparticle wires

silver inks with different size distributions to print flexible silver conductors, and concluded that a broad particle-size distribution helps improve the conductivity of printed silver conductors. Tang et al.[^21-22] proposed a microwave-assisted reaction method to prepare multiscale nanoparticle silver ink; the results showed that multiscale silver nanoparticles can enable printed silver conductors to obtain higher packing density and thus better conductive performance. However, the above studies focused only on the conductivity of printed silver conductors, and there are still relatively few studies on the mechanical properties of printed silver conductors in relation to the composition of nanoparticle silver inks. Liu et al.[^19] showed that silver conductors printed with inks containing a mixture of two nanoparticle sizes have better bending-fatigue resistance than silver conductors with a single particle size. Li et al.[^23] conducted bending-mechanics experiments on silver conductors printed with nanoparticle silver inks of different concentrations; the results showed that excessively high microstructural compactness leads to a decrease in the bending-fatigue resistance of the silver conductors.

Shang et al.[^24] studied the mechanical properties of silver conductors printed with nanoparticle silver inks of different size distributions. The results showed that as the average diameter of the silver nanoparticles in the conductor increased, the resistance of the silver conductor decreased, but its bending-deformation resistance and bending-fatigue performance also decreased correspondingly.

However, the mechanism by which the size and composition of nanoparticles in the conductor affect its stretchability and fatigue performance is still not very clear, and systematic studies are still lacking. Therefore, in this study, a multiscale nanoparticle structure of printed silver conductors is established by the finite element method. A cohesive model is applied to describe the interaction between particles, and the influence of different nanoparticle size distributions on the mechanical properties of printed silver conductors is analyzed.

1 Finite Element Modeling

After nanoparticle silver ink is printed on a flexible substrate and then sintered and solidified, a good bonding state is formed between particles. Figure 1 shows the microscopic morphology of a nanoparticle silver conductor after sintering and solidification.

Fig. 1 Physical image of the micro morphology of silver nanoparticle wires

In the finite element simulation process, in order to simplify the interaction between particles, all silver nanoparticles are simplified as spheres, and the

Fig. 2(a) Silver-particle particle-size normal distribution pattern

Figure 2: Fig. 2(a) Silver-particle particle-size normal distribution pattern

Fig. 2(b) Tangent packing effect of scaled particles

Figure 3: Fig. 2(b) Tangent packing effect of scaled particles

bonding force between particles is described using a cohesive model. Based on Python, a two-dimensional parametric model of the microstructure of the nanoparticle silver conductor is established. The specific procedure is as follows.

1) Define the average particle radius $\bar{r}$ and standard deviation S. According to the normal distribution, randomly generate a series of silver nanoparticles with different particle sizes, as shown in Fig. 2(a). The particle radius is denoted as r_i $(i = 1 \sim N)$, where N is the total

number.

2) Scale the radii of all silver particles proportionally according to $r_i' = r_i/\varphi$, $\varphi > 1$, and then use a random circular packing algorithm to densely pack the scaled particles within the specified region, ensuring that adjacent circles are tangent to each other, as shown in Fig. 2(b).

3) Enlarge the packed circles to restore their original sizes, $r_i = \varphi r_i'$. Import them into Abaqus and use Boolean operations to combine all circles into a single entity; identify the intersection points of all circles and draw the intersecting lines. Segment the circular particles and at the same time cut the edges, obtaining the particle-packing microstructural model shown in Fig. 2(c).

(a) Normal distribution pattern of silver-particle size

(b) Tangent packing effect of scaled particles

(c) Particle-packing microstructural model

(d) Meshing and insertion of zero-thickness cohesive elements between particles

图 2　二维纳米颗粒银导线有限元建模

Fig. 2　2D silver nanoparticle wire finite element modeling

4) Mesh the model, and use the “insert cohesive seams”function in the Abaqus software to insert zero-thickness cohesive elements at the intersecting lines

Fig. 2(c) Particle-packing microstructural model

Figure 4: Fig. 2(c) Particle-packing microstructural model

Fig. 2(d) Meshing and insertion of zero-thickness cohesive elements between particles

Figure 5: Fig. 2(d) Meshing and insertion of zero-thickness cohesive elements between particles

of all particles, as shown in Fig. 2(d).

All the above modeling procedures are implemented through Python scripts, enabling rapid finite-element modeling of the microstructure of silver conductive wires with different particle-size distributions. By assembling the parametrically generated silver conductive wire structure with the substrate, a finite-element model of a flexible silver conductive wire can be obtained.

In the simulation process, the stress–strain relationship of the silver particles [25–26] is

$$\sigma = \begin{cases} E\varepsilon, & \varepsilon \le \dfrac{\sigma_{\mathrm{Y}}}{E} \\ \sigma_{\mathrm{Y}} \left(\dfrac{\varepsilon}{\sigma_{\mathrm{Y}}/E} \right)^{N}, & \varepsilon > \dfrac{\sigma_{\mathrm{Y}}}{E} \end{cases} \tag{1}$$

where the elastic modulus is $E = 83$ GPa, the Poisson' s ratio is 0.36, the yield strength is $\sigma_{\mathrm{Y}} = 35$ MPa, and the hardening exponent is $N = 0.26$. The interaction between particles is described using a cohesive model. The substrate material is selected as a PI (polyimide) film, with elastic modulus $E_{\mathrm{sub}} = 3$ GPa. In the simulation process, the silver conductive wire and the substrate are considered to be ideally bonded, and interfacial fracture failure behavior between them is not considered.

2 Cohesive Model

The cohesive zone model (CZM) was first proposed by Dugdale [27]. By establishing a functional relationship model between interfacial traction and opening displacement, it characterizes the progressive damage and fracture process at an interface. After years of development, the cohesive model has become an important method for analyzing interfacial fatigue, damage, and fracture behavior in materials. When a cohesive model is used to simulate interfacial damage behavior, three characteristic parameters usually need to be determined: the initial stiffness of the element, the failure threshold, and the damage evolution parameter. The Abaqus finite-element software provides various methods for defining failure thresholds and damage evolution criteria. As shown in Fig. 3, this is a bilinear traction–displacement law, in which K_{n} and K_{t} denote the initial stiffnesses in the normal and tangential directions, respectively; the two are usually assigned the same value. δ_{n}^{0}, δ_{n}^{f} and δ_{t}^{0}, δ_{t}^{f} are the damage-initiation

Fig. 3(a) Normal traction–displacement law

Figure 6: Fig. 3(a) Normal traction–displacement law

Fig. 3(b) Tangential traction–displacement law

Figure 7: Fig. 3(b) Tangential traction–displacement law

displacement and fracture displacement in the normal and tangential directions, respectively.

(a) Normal traction–displacement law

(b) Tangential traction–displacement law

图 3　双线型内聚力模型

Fig. 3　Bilinear cohesive force model

Because the cohesive element is not an actual interlayer matrix, its stiffness

cannot be calculated using the actual substrate stiffness; in essence, it is a penalty stiffness. Turon et al.

derived the cohesive element stiffness as

$$K = \frac{\alpha E}{t} \qquad (2)$$

where E is the elastic modulus of the adjacent substrate layer; t is the thickness of the adjacent substrate layer; and α is the penalty factor, usually taken as $\alpha \gg 1$. In this study, α is set to 10, and t is taken as the average radius of the silver nanoparticle particles.

For two-dimensional finite element models, commonly used failure criteria include the maximum nominal stress/strain criterion and the quadratic nominal stress/strain criterion. In this study, the quadratic nominal stress criterion is adopted to define the damage-initiation behavior of the cohesive model, namely

$$\left\{\frac{\langle\sigma\rangle}{\sigma_{\max}}\right\}^2 + \left\{\frac{\tau}{\tau_{\max}}\right\}^2 = 1 \qquad (3)$$

where $\sigma_{\max}$ and $\tau_{\max}$ denote the normal and tangential stress thresholds at the onset of damage in the cohesive element, respectively; these are interface parameters that must be defined in the simulation. In this study, $\sigma_{\max} = \tau_{\max} = 150$ MPa.

The damage evolution of the cohesive element adopts an energy-based exponential evolution criterion, namely

$$D = \int_{\delta_{\mathrm{m}}^{0}}^{\delta_{\mathrm{m}}^{\mathrm{f}}} \frac{\sigma_{\mathrm{m}}}{G_{\mathrm{c}} - G_{0}} \, \mathrm{d}\delta_{\mathrm{m}} \qquad (4)$$

where δ_{m} is the equivalent opening displacement. For a two-dimensional model,

$$\delta_{\mathrm{m}} = \sqrt{\langle \delta_{\mathrm{n}} \rangle^{2} + \delta_{\mathrm{t}}^{2}};$$

σ_{m} is the equivalent tensile force; δ_{m}^{0} and $\delta_{\mathrm{m}}^{\mathrm{f}}$ are the equivalent opening displacements at damage initiation and at fracture, respectively; G_0 and G_{c} are the energy release rates at damage initiation and at complete fracture, respectively. For mixed normal-tangential modes,

$$G_{0} = G_{\mathrm{n}}^{0} + G_{\mathrm{t}}^{0} = \frac{1}{2} K_{\mathrm{n}} \langle \delta_{\mathrm{n}}^{0} \rangle^{2} + \frac{1}{2} K_{\mathrm{t}} \langle \delta_{\mathrm{t}}^{0} \rangle^{2} \qquad (5)$$

$$G_{\mathrm{c}} = 1 / \left[\left(\frac{m_{1}}{G_{\mathrm{n}}^{\mathrm{c}}} \right)^{\beta} + \left(\frac{m_{2}}{G_{\mathrm{t}}^{\mathrm{c}}} \right)^{\beta} \right]^{1/\beta} \qquad (6)$$

where $m_1 = G_{\mathrm{n}}/(G_{\mathrm{n}} + G_{\mathrm{t}})$, $m_2 = G_{\mathrm{t}}/(G_{\mathrm{n}} + G_{\mathrm{t}})$; G_{n} and G_{t} are the normal and tangential energy release rates, respectively; the exponential coefficient β is usually taken as 2; and $G_{\mathrm{n}}^{\mathrm{c}}$ and $G_{\mathrm{t}}^{\mathrm{c}}$ are the normal and tangential energy release rates at complete failure of the interface, respectively. In this study, $G_{\mathrm{n}}^{\mathrm{c}} = G_{\mathrm{t}}^{\mathrm{c}} = 1 \times 10^{-3}$ mJ/mm^2.

3 Results and Discussion

3.1 Simulation Analysis of the Mechanical Behavior of Nanoparticle Silver Conductive Wires

Figure 4 shows the established finite element model of the flexible silver conductive wire. Tensile displacement loading is applied to analyze its stress-strain behavior. To reduce the computational cost in the simulation, the selected nanoparticle silver conductive wire has dimensions of 1 μm × 2 μm. At the same time, considering both the accuracy of the computational results and the computational efficiency, the mesh size was finally unified as 10 nm, and the structure was partitioned. To analyze the influence of the substrate on the mechanical behavior of the silver film, finite element simulations were performed using different substrate thicknesses. During the simulation, because cohesive elements with damage evolution were used, implicit calculation is prone to non-convergence. Therefore, this study adopts an explicit algorithm and applies quasi-static loading to the silver conductive wire. During the tensile process, the tensile load F is borne jointly by the silver film and the substrate, and the loads are denoted as F_{Ag} and F_{sub}, respectively. Thus,

Fig. 4 Finite element model and loading diagram of flexible silver wire

Figure 8: Fig. 4 Finite element model and loading diagram of flexible silver wire

$$F = F_{\mathrm{Ag}} + F_{\mathrm{sub}} = \sigma_{\mathrm{Ag}} A_{\mathrm{Ag}} + \sigma_{\mathrm{sub}} A_{\mathrm{sub}} \qquad (7)$$

Figure 4 Finite element model and loading diagram of flexible silver wire

Fig. 4 Finite element model and loading diagram of flexible silver wire

Assuming that the substrate remains in the elastic stage during the loading process, the stress–strain relationship of the silver conductive wire can be derived from the above equation as

$$\sigma_{\mathrm{Ag}} = \frac{F}{A_{\mathrm{Ag}}} - \frac{E_{\mathrm{sub}} A_{\mathrm{sub}}}{A_{\mathrm{Ag}}} \varepsilon \qquad (8)$$

where A_{Ag} and A_{sub} are the areas of the silver film and the substrate, respectively. Since the stress–strain behavior of flexible silver conductive wires is essentially the same in the width direction during tensile and bending deformation, the stress in the width direction can be neglected. Moreover, the two-dimensional cohesive model is only applicable to plane-stress problems and cannot describe the influence of the stress in the width direction on interface failure behavior. Therefore, two-dimensional plane-stress elements are used in the simulation process, with the default thickness set to 1. Thus, Eq. (8) can be transformed into

$$\sigma_{\mathrm{Ag}} = \frac{F}{h} - \frac{E_{\mathrm{sub}} H_{\mathrm{sub}}}{h} \varepsilon \qquad (9)$$

That is, the stress–strain relationship of the nanosilver-particle silver film can be separated from the load–displacement data of the specimen.

Figure 5 shows the stress–strain curves obtained by tensile finite element simulation for silver conductive wires with the same particle-size distribution attached to substrates of different thicknesses. It can be seen from the figure that, compared with the silver conductive wire without a substrate, the silver conductive wire supported by a substrate exhibits better mechanical properties; with increasing substrate thickness, both the strength limit and ductility increase slightly. Moreover, when the substrate thickness exceeds twice the silver-film thickness, the stress–strain curve of the silver conductive wire changes hardly at all. Therefore, in subsequent simulations, the substrate thickness is set to twice the silver-film thickness.

Figure 5 Stress-strain curves of silver nanoparticle wires under different substrate thicknesses

Figure 5: Stress-strain curves of silver nanoparticle wires under different substrate thicknesses

Figure 9: Figure 5: Stress-strain curves of silver nanoparticle wires under different substrate thicknesses

Figure 6: Stress distribution cloud diagrams

Figure 10: Figure 6: Stress distribution cloud diagrams

Fig. 5 Stress-strain curves of silver nanoparticle wires under different substrate thicknesses

As shown in Fig. 6, the figure presents stress distribution cloud diagrams of silver wires without a substrate and with a substrate when loaded to different positions. It can be seen that, at the initial stage of loading, the stress distribution cloud diagrams of the two are basically the same, as shown in Fig. 6(a) and Fig. 6(c). This is consistent with the complete overlap of the stress-strain curves of the two before point A shown in Fig. 5. Figures 6(b) and 6(d) show the stress-field distributions of the two before fracture. It can be seen that the maximum stress value in the silver wire with a substrate (338.5 MPa) is slightly smaller than the maximum stress value in the silver wire without a substrate (352.5 MPa). This indicates that the presence of the substrate can, to a certain extent, suppress strain localization in the silver wire and improve the ductility of the silver wire.

(a) Stress distribution cloud diagram of a silver wire without substrate loaded to point A

(b) Stress distribution cloud diagram of a silver wire without substrate loaded to point B

(c) Stress distribution cloud diagram at point A when the substrate is 2 times the thickness of the silver film

(d) Stress distribution cloud diagram at point B when the substrate is 2 times the thickness of the silver film

Unit: $\mathrm{N}/\mu\mathrm{m}^2$

Figure 6 Stress distribution cloud diagrams of silver wires without substrate and with substrate thickness twice the silver-film thickness, loaded to A and B, respectively

Fig. 6 Stress distribution cloud diagram of silver wire without substrate and with substrate thickness twice the thickness of silver film loaded to A and B

3.2 Effect of particle size distribution on its mechanical properties

Porosity is an important parameter affecting the mechanical behavior of nanoparticle silver wires [29–32]. The radius scaling factor φ used in the

Figure 7: Stress-strain curves obtained from simulation analysis and tensile experiments

Figure 11: Figure 7: Stress-strain curves obtained from simulation analysis and tensile experiments

particle-stacking operation during finite element modeling is a major parameter affecting the porosity of the silver wire in the finite element model. At the same time, the average particle size $\bar{r}$ and standard deviation S also have certain effects on porosity. Figure 7 shows the stress-strain curves obtained from simulation analysis and tensile tests with an average particle size $\bar{r} = 50$ nm, standard deviation $S = 10$ nm, and scaling factor $\varphi = 1.1$ (SIM1–10 are simulation curves, and EXPT1–3 are experimental curves). It can be seen that the stress-strain curves of the simulation results and the experimental results have a relatively high degree of agreement, and the curves differ only slightly in the stress-decreasing stage. This verifies the rationality of the simulation model and the selected parameters.

Figure 7 Stress-strain curves obtained from simulation analysis and tensile experiments

Fig. 7 Stress-strain curves obtained from simulation analysis and tensile experiments

It can be seen that, due to the randomness of the silver-particle size distribution and stacking ···

···therefore, the mechanical properties of the silver wire also show a certain randomness. In order to study the variation trend of the mechanical properties of the silver wire under different modeling parameters, each group of parameters was subjected to 10 random modeling analyses. The maximum nominal stress during the tensile process of the silver wire and its corresponding nominal strain were taken as the fracture strength and fracture strain of the silver wire, and the influence of the microstructural parameters of the nano-particle silver wire on the mechanical behavior of the silver wire was analyzed through statistical regularity.

As shown in Fig. 8(a), when the mean particle size is $\bar{r} = 50$ nm and the standard deviation is $S = 10$ nm, the fracture strength and fracture strain of the silver wire obtained by modeling simulation vary with the particle-size scaling coefficient φ. As the scaling coefficient increases, both the fracture strength and fracture strain of the silver wire increase significantly. Further, the porosity was calculated from the actual effective area of the silver wire by simulation software, and the results are shown in Fig. 8(b). It can be seen that the porosity of the silver wire shows an approximately linear decreasing trend with the increase of the particle-size scaling coefficient, verifying the positive correlation between the mechanical properties of the printed silver wire and the density of its microstructure.

Fig. 8(a)

Figure 12: Fig. 8(a)

Fig. 8(b)

Figure 13: Fig. 8(b)

(a) Variation curves of the fracture strength and fracture strain of silver-wire fracture with the particle-size scaling coefficient

(b) Variation curve of the porosity of the silver wire with the particle-size scaling coefficient

Fig. 8 Curves of fracture strength, fracture strain, and porosity of the silver wire with particle-size scaling coefficient

Fig. 8 Curve of fracture strength, fracture strain, and porosity with particle size scaling coefficient of silver wire

Using normally distributed particles with different mean particle sizes ($\bar{r} = 30 \sim 80$ nm, $S = 0.2\bar{r}$, $\varphi = 1.1$), modeling simulations were carried out for the nano-particle silver wire. The resulting variation curves of fracture strength, fracture strain, and porosity of the silver wire with mean particle size are shown in Fig. 9. From Fig. 9(a), it can be seen that the change in the mean particle size of the silver particles has almost no influence on the fracture strength and fracture strain of the silver wire. Further analysis of the variation trend of the porosity of the silver wire, as shown in Fig. 9(b), shows that with the change in the mean particle size of the silver particles, the microporosity of the silver wire basically remains unchanged. This is consistent with the conclusion in packing theory that the packing density of spheres is independent of sphere diameter.

(a) Variation curves of the fracture strength and fracture strain of silver-wire fracture with mean particle size

(b) Variation curve of the porosity of the silver wire with mean particle size

Fig. 9 Variation curves of the fracture strength and fracture strain of silver-wire fracture and porosity with mean particle size

Fig. 9 Curve of fracture strength, fracture strain, and porosity with average particle size for silver wire fracture

Furthermore, nano-particle silver wires were modeled and simulated using the same particle size but different particle-size standard deviations ($\bar{r}$ = 50 nm,

Fig. 9(a)

Figure 14: Fig. 9(a)

Fig. 9(b)

Figure 15: Fig. 9(b)

Figure 10(a): Curves of fracture strength and fracture strain of silver wire versus particle-size standard deviation

Figure 16: Figure 10(a): Curves of fracture strength and fracture strain of silver wire versus particle-size standard deviation

$S = 0 \sim 45$ nm, $\varphi = 1.1$), and the results are shown in Fig. 10. It can be seen that, as the standard deviation of the silver particles increases from 0 to 45 nm, the fracture strength and fracture strain of the silver wire exhibit relatively obvious fluctuations, as shown in Fig. 10(a). Moreover, when the particle-size standard deviation increases from 10 nm to 45 nm, the porosity of the silver wire shows an obvious decreasing trend and gradually tends to stabilize, as shown in Fig. 10(b). When the particle-size standard deviation is 0, the structure belongs to uniform sphere packing, which forms a very regular microstructure and a relatively low porosity, giving the silver wire very high fracture strength and fracture···

strain at fracture.

(a) Curves of the fracture strength and fracture strain of silver wire as functions of the particle-size standard deviation

(b) Curve of the porosity of silver wire as a function of the particle-size standard deviation

Figure 10 Variation curves of the fracture strength, fracture strain, and porosity of silver wire with the particle-size standard deviation

Fig. 10 Curve of fracture strength, fracture strain, and porosity of silver wire with standard deviation of particle size

As shown in Fig. 11(a), when the particle-size standard deviation is 5 nm, the microstructure obtained by finite-element modeling of the silver wire shows that both the particle size and the pores are essentially uniformly distributed. Therefore, during tensile deformation, the stress–strain distribution also tends to be uniform, and at this time the silver wire exhibits good ductility and fracture strength. When the particle-size standard deviation gradually increases (5–15 nm), the silver wire begins to transform from a relatively regular microstruc-

Figure 10(b): Curve of porosity of silver wire versus particle-size standard deviation

Figure 17: Figure 10(b): Curve of porosity of silver wire versus particle-size standard deviation

Figure 11(a): Microstructure at S=5 nm

Figure 18: Figure 11(a): Microstructure at S=5 nm

Figure 11(b): Microstructure at S=15 nm

Figure 19: Figure 11(b): Microstructure at S=15 nm

ture to a disordered microstructure, as shown in Fig. 11(b). During loading, regions with relatively high porosity are prone to localization of stress-strain behavior, causing a clear decreasing trend in the fracture strength and fracture strain of the silver wire. As the particle-size standard deviation further increases, the difference in the silver-particle diameters becomes larger, so that silver particles with smaller diameters can be located in the gaps formed by the packing of larger silver particles. This increases the microscopic compactness of the silver wire, and the bonding between particles becomes tighter, as shown in Fig. 11(c). Therefore, the fracture strength and fracture strain of the silver wire show a certain degree of enhancement. When the standard deviation is too large (30–45 nm), the particle-size difference further increases, the disorder of the microstructure increases sharply, and larger pores are readily formed around the large particles, as shown in Fig. 11(d). This makes the silver wire more likely to develop strain localization during extended deformation, thereby reducing its fracture strength and fracture strain.

(a) $S = 5$ nm, relatively uniform microstructure

(b) $S = 15$ nm, increased microstructural disorder

(c) $S = 25$ nm, a large number of small particles fill the gaps among large particles

(d) $S = 35$ nm, relatively large pores form around large particles

Figure 11 Microstructure diagrams of silver wire obtained by modeling with different particle-size standard deviations

Fig. 11 Microstructure diagram of silver wire obtained by modeling the standard deviation of different particle sizes

3.3 Mechanical properties of silver wire with a bimodal particle-size distribution

The finite-element analysis results show that, for nanoparticle silver wire whose particle sizes follow a single normal distribution, changes in the average particle

Figure 11(c): Microstructure at S=25 nm

Figure 20: Figure 11(c): Microstructure at S=25 nm

Figure 11(d): Microstructure at S=35 nm

Figure 21: Figure 11(d): Microstructure at S=35 nm

Figure 13

Figure 22: Figure 13

size have almost no effect on the microscopic porosity and mechanical properties of the silver wire. An increase in particle-size standard deviation can, to a certain extent, improve the microscopic porosity of the silver wire, but the improvement in mechanical properties is quite limited. The main reason is that increasing the particle-size standard deviation allows more small particles to fill the gaps among large particles, but at the same time it also causes relatively large pores to form around more large particles.

large pores. To solve this problem, this section uses two groups of particles with different average particle sizes for mixed modeling, and studies the effect of a bimodal normal particle-size distribution on the mechanical behavior of nano-silver wire. Figure 12 shows an ideal model in which small particles fill the gaps between large particles. According to the geometric relationship, $r_1 = (2/\sqrt{3} - 1)R$, $r_2 = (\sqrt{2} - 1)R$. When the small-particle radius $r \in [r_1, r_2]$, a relatively ideal effect can be obtained in which small particles fill the pores between large particles, increasing the compactness. Therefore, small particles with particle sizes following a random normal distribution (average particle size $r = 7.5 \sim 20$ nm, standard deviation $0.2r$) and large particles with particle sizes following a random normal distribution (average particle size $R = 50$ nm, standard deviation $0.2R$) are mixed according to different number ratios, and random stacking modeling is carried out with a particle-size scaling factor $\varphi = 1.1$, to study the influence law of the microstructure of nano-silver wire on its mechanical properties.

(a) Triangular stacking model

(b) Quadrilateral stacking model

Figure 12 Ideal model of small particles filling gaps between large particles

Fig. 12 Ideal model of small particles filling large particle gaps

Figure 13 shows the variation curves of the modeled microscopic porosity of silver wire with the average particle size of small particles and the mixing ratio. The mixing ratio is the ratio of the number of small particles to the number of large particles. A mixing ratio of 0 indicates stacking modeling using only large particles with a single average particle size of 50 nm.

Figure 13 Variation curves of the microscopic porosity of silver wire with the average particle size of small particles and the mixing ratio

Fig. 13 Micro porosity curve of silver wire as a function of average particle size and mixing ratio of small particles

It can be seen that, when the average particle size of small particles is 7.5 nm and 10 nm, as the number of small particles increases, the porosity of the silver wire decreases significantly; whereas when the average particle size of small particles is $12.5 \sim 20$ nm, the porosity of the silver wire shows a trend of first decreasing and then slowly increasing. This is because, during the random stacking process, the smaller the particle size of the small particles, the more easily they fill the voids around the large particles, causing the porosity of the silver wire to decrease significantly, as shown in Fig. 14(a). However, when the small particles have larger particle sizes and are more numerous, the small particles instead separate the large particles, forming more voids near the large particles, as shown in Fig. 14(b), resulting in an upward trend in the microscopic porosity of the silver wire.

(a) Microstructure diagram with an average small-particle size of 10 nm; porosity is 3.38%

(b) Microstructure diagram with an average small-particle size of 20 nm; porosity is 4.99%

Figure 14 Microstructure diagrams formed by random stacking with a bimodal normal particle-size distribution, for small-particle average particle sizes of 10 nm and 20 nm, respectively, and a mixing ratio of 3

Fig. 14 Microstructure diagram of small particles with average particle size of 10 nm and 20 nm, mixing ratio of 3, randomly stacked with double peak normal distribution of particle size

Figure 15 shows the variation curves of the fracture strength and fracture strain of the silver wire with the average particle size of small particles and the mixing ratio. It can be seen that when the average particle size of the small particles is 7.5 nm and 10 nm, the fracture strength and fracture strain of the silver wire both increase significantly with the increase in the number of small particles; whereas when the average particle size of small particles is $12.5 \sim 20$ nm, the fracture strength and fracture strain of the silver wire overall show a decreasing trend as the number of small particles increases.

The reason is that when the average particle size of the small particles is too large, only a relatively small number of small particles fill the voids in the large-particle stacking, while most small particles separate the large particles during random stacking, forming more pores, as shown in Fig. 14(b), resulting in a decline in mechanical properties. When the average particle size is less than 10 nm, the small particles can be better embedded in the stacking gaps of the large particles, and the large particles still maintain a good bonding state with each other, as shown in Fig. 14(a); therefore, the mechanical properties are better.

(a) Variation curve of the fracture strength of silver wire with the average particle size and mixing ratio of small particles

Fig. 15(a) Curve of fracture strength of silver wire as a function of the average particle size and mixing ratio of small particles

Figure 23: Fig. 15(a) Curve of fracture strength of silver wire as a function of the average particle size and mixing ratio of small particles

Fig. 15(b) Curve of fracture strain of silver wire as a function of the average particle size and mixing ratio of small particles

Figure 24: Fig. 15(b) Curve of fracture strain of silver wire as a function of the average particle size and mixing ratio of small particles

(b) Variation curve of the fracture strain of silver wire with the average particle size and mixing ratio of small particles

Fig. 15 Curve of the fracture strength and strain rate of silver wire as a function of the average particle size and mixing ratio of small particles

4 Conclusion

1) In this study, a random packing algorithm using circular particles with a normal particle-size distribution was adopted to conduct two-dimensional finite element modeling of the microstructure of nanoscale-particle silver wire. The bonding strength between particles was characterized by a cohesive-force model, providing a new method for investigating the influence of the microstructure of nanoscale-particle silver wire on its mechanical reliability.

2) Finite element simulation was used to investigate the effects of the average particle size and standard deviation of normally distributed nanoparticles on the microscopic porosity and mechanical properties of silver wire formed by random packing. The results show that the standard deviation of particle size is the main factor affecting the porosity of silver wire. The larger the standard deviation of particle size, the denser the microstructure formed. The average particle size has almost no effect on porosity. The mechanical properties of silver wire are basically negatively correlated with porosity; however, an excessively large standard deviation makes it easy for larger pores to form around large-diameter particles, intensifying the occurrence of strain localization and thereby leading to a decline in mechanical properties.

3) Particles with a bimodal normal distribution, in which the average particle size of large particles is 50 nm and that of small particles is 7.5–20 nm, were modeled. The influence of the average particle size and mixing ratio of small particles on the microscopic porosity and mechanical properties of silver wire was analyzed. The results show that when the average particle size of the small particles is 7.5 nm and 10 nm, the microscopic porosity of

the silver wire decreases as the number fraction of small particles increases; meanwhile, the mechanical properties are significantly improved.

References:

[1] Sharma N, Nair N M, Nagasarvari G, et al. A review of silver nanowire-based composites for flexible electronic applications[J]. Flexible and Printed Electronics, 2022, 7(1): 014009.

[2] Sircar A, Kumar H. An introduction to flexible electronics: manufacturing techniques, types and future[J]. Journal of Physics: Conference Series, 2021, 1913(1): 012047.

[3] Wang S, Feng Y, Zhang H, et al. Highly stable and printable Ag NWs/GO/PVP composite ink for flexible electronics[J]. Flexible and Printed Electronics, 2021, 6(2): 024002.

[4] Li D D, Lai W Y, Feng F, et al. Post-treatment of screen-printed silver nanowire networks for highly conductive flexible transparent films[J]. Advanced Materials Interfaces, 2021, 8(13): 2100548.

[5] Zhou Z L, Yang Y C, Liu H H. A braille reading system based on electrotactile display with flexible electrode array[J]. IEEE/CAA Journal of Automatica Sinica, 2022, 9(4): 735-737.

[6] Chen S Y, Guan Y W, Li Y, et al. A water-based silver nanowire ink for large-scale flexible transparent conductive films and touch screens[J]. Journal of Materials Chemistry C, 2017, 5(9): 2404-2414.

[7] Jeong H, Noh Y, Kim G Y, et al. Roll-to-roll processed silver nanowire/silicon dioxide microsphere composite for high-accuracy flexible touch sensing application[J]. Surfaces and Interfaces, 2022, 30: 101976.

[8] Shi Shiming, Li Yuanyuan, Zheng Meizhu, et al. Current situation and development of touch sensor technology used in flexible AMOLED display[J]. Chinese Journal of Liquid Crystals and Displays, 2022, 37(4): 459-466 (in Chinese).

[9] Rosati G, Ravarotto M, Scaramuzza M, et al. Silver nanoparticles inkjet-printed flexible biosensor for rapid label-free antibiotic detection in milk[J]. Sensors and Actuators B: Chemical, 2019, 280: 280-289.

[10] Zeng Weichen, Liu Qian. Research progress of flexible sensors based on conductive fiber[J]. Transducer and Microsystem Technologies, 2021, 40(1): 1-4 (in Chinese).

[11] Chen S W, Qi J M, Fan S C, et al. Flexible wearable sensors for cardiovascular health monitoring[J]. Advanced Healthcare Materials, 2021, 10(17): 2100116.

[12] Chen R, Luo T, Geng D, et al. Facile fabrication of a fast-response flexible

temperature sensor via laser reduced graphene oxide for contactless human-machine interface [J]. Carbon, 2022, 187: 35-46.

[13] Angmo D, Larsen-olsen T T, Jørgensen M, et al. Roll-to-roll inkjet printing and photonic sintering of electrodes for ITO free polymer solar cell modules and facile product integration [J]. Advanced Energy Materials, 2013, 3(2): 172-175.

[14] Jia Yingna, Liu Xingxing, Lu Yun, et al. Flexible electrode assembled from different microstructures [J]. Progress in Chemistry, 2019, 31(2): 464-474.
Jia Yingna, Liu Xingxing, Lu Yun, et al. Flexible electrode assembled from different microstructures [J]. Progress in Chemistry, 2019, 31(2): 464-474 (in Chinese).

[15] Tam K C, Kubis P, Maisch P, et al. Fully printed organic solar modules with bottom and top silver nanowire electrodes [J]. Progress in Photovoltaics, 2022, 30(5): 528-542.

[16] Maisch P, Tam K C, Lucera L, et al. Inkjet printed silver nanowire percolation networks as electrodes for highly efficient semitransparent organic solar cells [J]. Organic Electronics, 2016, 38: 139-143.

[17] Zhao Jia, Liu Lifeng, Zhang Ying. Synthesis of silver nanoparticles loaded onto a structural support and their catalytic activity [J]. Acta Physico-Chimica Sinica, 2015, 31(8): 1549-1558.
Zhao Jia, Liu Lifeng, Zhang Ying. Synthesis of silver nanoparticles loaded onto a structural support and their catalytic activity [J]. Acta Physico-Chimica Sinica, 2015, 31(8): 1549-1558 (in Chinese).

[18] Du T H, Tang C L, Xing B, et al. Conductive ink prepared by microwave method: effect of silver content on the pattern conductivity [J]. Journal of Electronic Materials, 2019, 48(1): 231-237.

[19] Liu Z Y, Ji H J, Wang S, et al. Enhanced electrical and mechanical properties of a printed bimodal silver nanoparticle ink for flexible electronics [J]. Physica Status Solidi (a), 2018, 215(14): 1800007.

[20] Ding J, Liu J, Tian Q Y, et al. Preparing of highly conductive patterns on flexible substrates by screen printing of silver nanoparticles with different size distribution [J]. Nanoscale Research Letters, 2016, 11(1): 412.

[21] Tang C L, Xing B, Hu G S, et al. A facile microwave approach to the fast-and-direct production of silver nano-ink [J]. Materials Letters, 2017, 188: 220-223.

[22] Tang C L, Zheng S H, Wang F, et al. Microwave-assisted two-steps method for the facile preparation of silver nanoparticle conductive ink [J]. Journal of Materials Science-Materials in Electronics, 2019, 30(12): 11588-11597.

[23] Li C, Sun Q, Tang C L, et al. A two-step method to prepare silver nanoparticles ink for improving electrical and mechanical properties of printed silver wire [J]. Materials Express, 2021, 11(4): 516-523.

[24] Shang Y B, Sun Q, Lu Y B, et al. Improvement of electrical and mechanical properties of printed silver wire by adjusting particle size distribution of multi-scale silver nanoparticle ink [J]. Journal of Electronic Materials, 2022, 51(11): 6503-6511.

[25] Smith D R, Fickett F R. Low-temperature properties of silver [J]. Journal of Research of the National Institute of Standards and Technology, 1995, 100(2): 119-171.

[26] Li T, Suo Z G. Ductility of thin metal films on polymer substrates modulated by interfacial adhesion [J]. International Journal of Solids and Structures, 2007, 44(6): 1696-1705.

[27] Dugdale D S. Yielding of steel sheets containing slits [J]. Journal of the Mechanics and Physics of Solids, 1960, 8(2): 100-104.

[28] Turon A, Dávila C G, Camanho P P, et al. An engineering solution for mesh size effects in the simulation of delamination using cohesive zone models [J]. Engineering Fracture Mechanics, 2007, 74(10): 1665-1682.

[29] Kim S, Won S, Sim G D, et al. Tensile characteristics of metal nanoparticle films on flexible polymer substrates for printed electronics applications [J]. Nanotechnology, 2013, 24(8): 085701.

[30] Sim G D, Won S, Lee S B. Tensile and fatigue behaviors of printed Ag thin films on flexible substrates [J]. Applied Physics Letters, 2012, 101(19): 191907.

[31] Shao Zhushan, Jiang Yansong, Wei Wei, et al. Numerical analysis of multi-field coupling between mortar-aggregate under microwave radiation [J]. Chinese Journal of Applied Mechanics, 2026, 43(1): 123-133.
Shao Zhushan, Jiang Yansong, Wei Wei, et al. Numerical analysis of multi-field coupling between mortar-aggregate under microwave radiation [J]. Chinese Journal of Applied Mechanics, 2026, 43(1): 123-133 (in Chinese).

[32] Jiang Weizhong, Zhang Yi, Zhu Yilin, et al. Research progress and prospect of functional auxetic metamaterials [J]. Chinese Journal of Applied Mechanics, 2025, 42(3): 494-510.
Jiang Weizhong, Zhang Yi, Zhu Yilin, et al. Research progress and prospect of functional auxetic metamaterials [J]. Chinese Journal of Applied Mechanics, 2025, 42(3): 494-510 (in Chinese).

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