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Microstructure Evolution and Deformation Behavior of Gold Cladding Silver Composite Bonding Wire

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Abstract: The microstructure and mechanical property of gold cladding silver composite bonding wire under different true strains were characterized by metallographic microscope, double beam electron microscope, high-low temperature tensile tester and nano-indentor. The results show that the silver alloy core of gold cladding silver composite bonding wire evolves from cellular dendrite to fiber structure along the drawing direction. The gold cladding layer is uniform and continuous and the transition layer near the interface always keeps fine equiaxed or spherical grains during the deformation process. Inconsistent size change among each component is observed during deformation, and the fitted size change constant is not proportional to the change of wire diameter. Microhardness, tensile strength and elongation increase with the increase of deformation amount. During the uniaxial drawing process, the unidirectional tensile strain becomes a complex two-dimensional stress state due to the interaction between each component of the composite wire. Thus the plasticity and toughness of the material can be improved because the alternating stress inhibits the nucleation of crack.

Key words: layered composite material; gold cladding silver composite bonding wire; microstructure evolution; deformation behavior

Micro-nano composite bonding wire composed of two or more components in the form of surface cladding presents advantages of high strength, excellent chemical stability and low price [1-3]. These wires thus have become the critical materials in the interconnection structure of high-performance microelectronic packaging. Due to its plentiful and controllable microstructure characteristics, such as crystal structure, modulation structure parameters and interface structure/characteristics (interface mismatch and orientation relationship), the cladding lamellar composite bonding wire becomes an ideal material for studying the coordinated deformation of different components with large plastic deformation behavior. Currently, the composite materials used in microelectronic packaging bonding wire include gold cladding silver composite bonding wire[4,5] and palladium cladding copper wire[6-8]. Tseng[9] tested the tension and current density of gold cladding silver composite bonding wire by electrical tensile test, evaluated the strength change during electrification, and revealed the fracture mode. Lim[10] studied the distribution of palladium during the ball-forming process and growth of intermetallic compounds at the soldering interface. However, the above research results mainly focus on the service performance and reliability of bonding wires, and rarely discuss the microstructure and deformation coordination in the preparation process. The study of the deformation behavior of the cladding layer and the core material on the mesoscopic scale is of great significance for revealing the service failure mechanism of the multilayer composite wire and exploring the intrinsic deformation behavior of the material. At the same time, it is the central goal of materials science and engineering research to apply the correlation between material properties and efficiency, microstructure and corresponding process methods to engineering structural components [11].

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In this study, microstructure evolution, and mechanical performance parameters (such as strength and ductility) during the preparation process of gold cladding silver composite bonding wires were studied, and the mechanical properties of layered composite bonding wires were discussed. The size effect and its intrinsic physical mechanism, the deformation coordination mechanism of the component, and the deformation mechanism during large plastic drawing of the layered composite materials were explored.

1 Experiment

A gold cladding silver composite bonding wire with silver alloy as core material produced by Sino-platinum Metals Co., Ltd was studied in this work. Composition of the silver alloy was 0.1wt% ~5wt% Cu, 0.001wt% ~0.01wt% Sn, and the balance silver. The gold cladding silver ingot (Φ15 mm) was prepared using a composite continuous casting furnace, preheated at 300~500 °C for 1~2 h under charcoal protection, hot extruded into a rod of Φ6 mm, and then cold drawn and processed into a Φ0.020 mm sample. Samples were taken when the true strain η=2.25, 4.76, 7.22, 10.41, 11.12, 11.94, 12.56, 13.24 ($\eta=\ln(A_0/A)$, where A_0 and A represent cross-sectional area of the composite at initial stage and after deformation, respectively. The cross-section and longitudinal section of the as-cast, η=4.76 and η=13.24 samples were taken by electric discharge wire cutting. Metallographic structure was observed using XWJ-02 normal material microscope after corrosion using mixed solution of ferric chloride and hydrochloric acid for 3~5 s. The cross and vertical sections of the gold wire sample (η=13.24) were cut using the ion beam (FIB) in FEI Versa 3D, a double-beam electron microscope, and the microstructure of the gold wire sample was characterized by electron back scattering diffraction (EBSD). INSTRON LEGEND 2344 high-low temperature tensile tester was used to test the breaking load and elongation under different true strain conditions. The gauge length was 100 mm, and the testing speed was 50 mm/min. Hysitron nanometer indenter was used to test the hardness of the gold cladding and the silver alloy core material with a load of 4 mN.

2 Results and Discussion

2.1 Microstructure

Microstructure of the gold cladding silver composite bonding wire was observed at different true strains. Fig. 1 shows the metallographic structure of the ingot. The cross section is composed of cellular dendrites and cellular grains, and the longitudinal section presents dendrite morphology growing along the axial direction. The grain size of cross section was measured, and the mean value is 43.1 μm.

Fig.2 shows the as drawn and annealed microstructures of gold cladding silver composite bonding wires at true strain of 4.76. Annealing was conducted at 500 °C for 0.5 h. As can be seen from Fig.2b, three areas are divided from the edge to the center, namely the gold cladding layer, the alloy transition layer and the silver alloy core. After multi-way drawing,

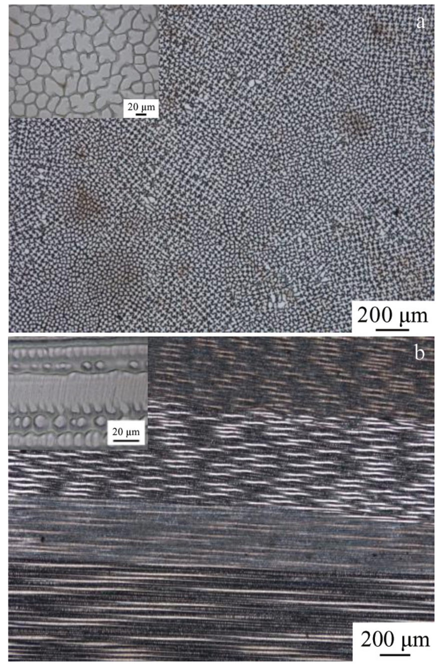

Fig.1 Metallographic images of as-cast gold cladding silver composite bonding wire: (a) cross section; (b) longitudinal section

dendrite crystals of ingots are broken and extended along the stretching direction to form fibrous structure. In the cold drawing process, the silver alloy core and the gold cladding layer contact and press each other. Due to the statistical distribution of polycrystalline orientation, some crystallographic orientations coincide accidentally. Or due to energy fluctuations, the energy limit is broken at high energies to form metal bonds, resulting in point bonding. Therefore, the alloy transition layer is formed, but the interface with strong binding force cannot be formed due to the low temperature during processing, so diffusion annealing process is needed to improve the interface binding force. After annealing, the core of the wire starts to recrystallize, and a large number of recrystallized grains appear. From the longitudinal section (Fig. 2d), incomplete recrystallization can be seen after annealing, and parts of the fibrous drawn structure remain. The transition layer is completely recrystallized with obvious polygon morphology after annealing. The grains close to the interface are smaller than those close to the core. According to the Hall-Petch formula, yield strength of materials is inversely proportional to grain size. Such refined grains embedded in the composite structure will improve toughness of the cladding layer and the stress distribution, which makes the cladding layer have higher hardness, strength and fracture toughness[12]. Fig.3 shows the processed and annealed morphologies of the gold cladding layer (along the drawing direction). Under the action of drawing stress, the gold cladding layer forms fibrous structure with uniform fiber size. After annealing, the grains begin to recrystallize to form equiaxed grain structure.

Fig. 4 is the microstructures of gold cladding silver composite bonding wire when true strain η=13.24. It can be

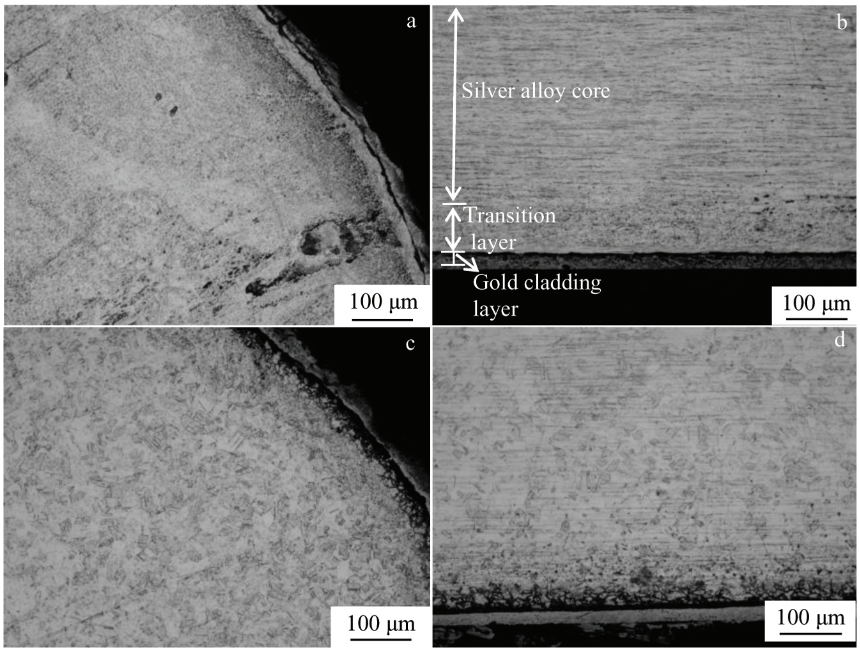

Fig.2 Metallographic images of as drawn (a, b) and annealed (c, d) gold cladding silver composite bonding wire when η=4.76: (a, c) cross section and (b, d) longitudinal section

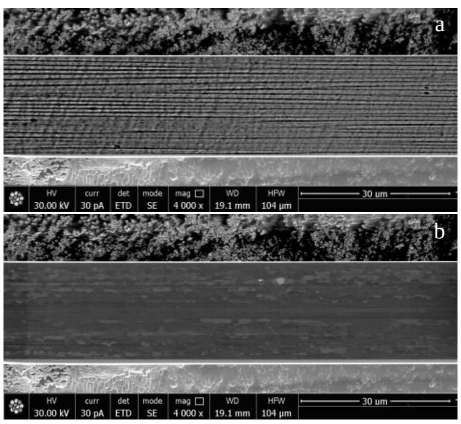

Fig.3 Morphologies of gold cladding layer in processed (a) and annealed (b) conditions

seen from the cross section that the grains are small, polygonal and even nearly spherical after large plastic drawing. The grain size in the center is 300~600 nm, while that of the edge grains is only 10~200 nm. The black lines mark the interface between the gold cladding and the silver alloy core. It can be seen from the longitudinal section that the grains in the center are longer, and the longest grains exceed 25 μm, while that at the edge are shorter and the shortest grains are only 1 μm. From the microstructure of gold cladding silver composite bonding wire, it can be seen that the stress is not uniform at the center and the edge during large plastic drawing.

2.2 Size change of each phase of gold cladding silver composite bonding wire

The size of each phase of gold cladding silver composite

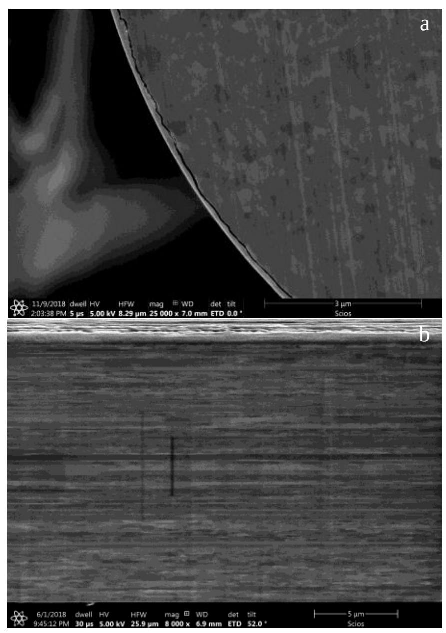

Fig.4 Microstructures of gold cladding silver composite bonding wire at η =13.24: (a) cross section in the lower part and (b) longitudinal section

bonding wire was measured under different deformation amounts, and the relationship between average size and deformation amount is shown in Fig. 5. As can be seen, the average thickness (t_{Au}) of gold cladding layer and average diameter (t_{Ag}) of silver alloy core decrease with the increase of true strain. The curves are fitted by power function, and the relationships between the gold cladding thickness, silver alloy

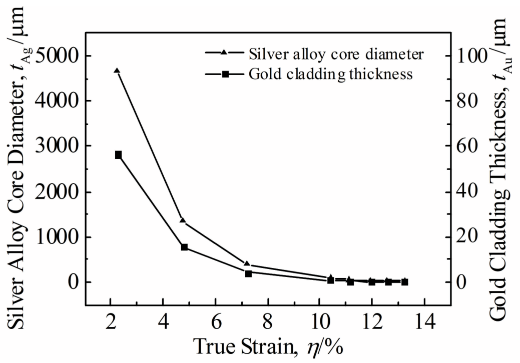

Fig.5 Size of each phase of the gold cladding silver composite bonding wire under different deformation amounts

core diameter and true strain are obtained.

$$t_{Ag} = -2.52 + 14123.66\exp(-0.49\eta) \tag{1}$$

$$t_{Au} = -0.05 + 179.37\exp(-0.51\eta) \tag{2}$$

According to the definition of true strain η, $\eta = \ln(A_0/A) = \ln(d_0^2/d^2) = 2\ln(d_0/d)$, and assuming that the deformation of each phase size is proportional to the deformation of the sample, then:

$$\frac{t_0}{t} = \frac{d_0}{d} = \exp\left(\frac{\eta}{2}\right) \tag{3}$$

Therefore, when the deformation of each phase of the wire is uniform, the relationship between the size of each phase and the true strain should be:

$$t = t_0 \exp(-0.5\eta) \tag{4}$$

However, the deformation of each phase inside the wire is not uniform, and change of the size of each phase is not proportional to the change of the diameter of the sample. Therefore, the coefficient of η obtained by fitting Eq.(1) is not equal to 0.5.

2.3 Microhardness of each phase of gold cladding silver composite bonding wire

Fig. 6 shows the microhardness of each phase of the gold cladding silver composite bonding wire under different true strains. It can be seen that microhardness of the gold cladding layer dynamically changes and slightly increases with the increase of true strain, and the microhardness of the core material shows an increasing trend. Due to the thin thickness of the gold cladding layer, the tensile structure is cut off by the interface and the transition layer in the deformation process, which reduces the work hardening increment and results in a small increase of microhardness. The center of the core material is hardly affected by the gold cladding layer and the interface. As the true strain increases, the fiber structure increases, the texture is formed, and the hardness increases.

2.4 Room-temperature tensile property of gold cladding silver composite bonding wire

Fig. 7 shows the variation of breaking strength and elongation of gold cladding silver composite bonding wire with the true strain. As can be seen, both the breaking strength and elongation of the gold cladding silver composite bonding wire increase with the increase of true strain. The traditional homogeneous materials are subjected to uniaxial tensile stress during the tensile process, but the stress state of layered composites is changed by the mutual binding of the components. When the contraction of the surface layer is restricted by the central part, the surface layer is subjected to a lateral tensile stress. Since there is no external lateral force, the tensile stress of the surface layer is balanced by the compressive stress of the inner part. In the process of tension, the unidirectional tensile stress gradually changes into a complex two-dimensional stress state. The surface layer is subjected to the tensile stress, while the inner part is subjected to the compressive stress. This alternating stress state passivates the crack tip, and the existence of compressive stress can also effectively inhibit the nucleation of cracks, thus improving the plasticity and toughness of materials[13]. Normally, stress should include residual stress, applied tensile stress, lateral stress due to Poisson ratio mismatch, etc. In the stage of linear elastic deformation, the stress intensity is different because of different elastic modulus of each component of layered composites. In order to ensure continuous deformation of the material, the interface will play a role of stress transfer and redistribution[14-16]. At the bonding interface, with the increase of strain rate, different deformation resistance on both sides needs to be adapted to achieve continuous deformation without causing material

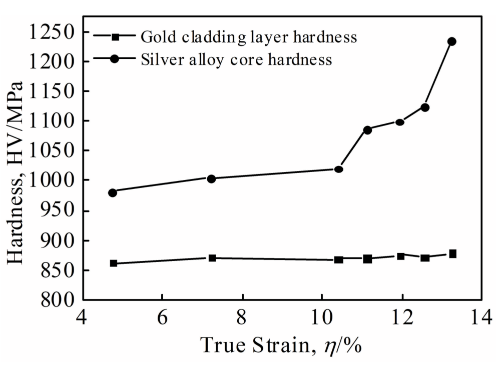

Fig.6 Hardness of cladding layer and core of gold cladding silver composite bonding wires at different true strains

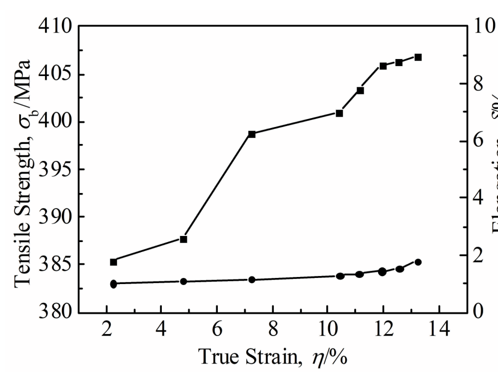

Fig.7 Relationship between tensile property and true strain of gold cladding silver composite bonding wires

damage. The main coordination mechanism relies on the slip of the bonding interface and nearby grains to achieve deformation.

In conclusion, due to the structural difference of each component and the presence of interface, the structure of the core material evolves from cellular dendrites to fibrous structure, and the transition layer presents cellular grains in the process of tensile deformation. Compared with homogeneous materials, the deformation behavior of gold cladding silver composite bonding wires is complex. The deformation stress is diverse and mutually restricted, and the interface plays the role of stress transfer and redistribution. This stress state will inhibit the nucleation of the crack, so the gold cladding silver composite bonding wire has good plasticity and toughness.

3 Conclusions

1) The microstructure of the core material of gold cladding silver composite bonding wire along the drawing direction transforms from cellular dendrite to fiber structure. The transition layer near the interface maintains fine cellular grains and the gold layer is uniform and continuous during the deformation.

2) In the process of tensile deformation, the phases of gold cladding silver composite bonding wire are not uniform and mutually restricted, and the change of size is not proportional to the change of sample diameter.

3) With the increase of true strain, microhardness of the gold cladding layer changes dynamically and increases slightly, and the microhardness of the core material shows an increasing trend. The increase trend of cladding layer microhardness is small due to the influence of interface and transition layer.

4) The breaking load and elongation of gold cladding silver composite bonding wire increase with the increase of true strain. In the process of uniaxial tension, the mutual constraint of each component of the wire changes stress state of the material, and the unidirectional tensile stress changes to a complex two-dimensional stress state. This alternating stress state inhibits the nucleation of cracks, improving the plasticity and toughness of gold cladding silver composite bonding wire.

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金包银复合键合丝的组织演变及变形行为

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摘　要：采用金相显微镜、双束离子显微镜、高低温拉力仪及纳米压痕仪对不同真应变条件的金包银复合键合丝的组织和力学性能进行表征，研究了金包银复合键合丝的组织结构演变、力学性能及变形行为特点。结果表明：金包银复合键合丝的银合金芯材沿着拉伸方向从胞状树枝晶演变为纤维组织，靠近界面的过渡层始终保持细小的等轴晶或球状晶粒，金包覆层在变形过程中均匀连续。各组分在变形过程中尺寸变化不一致，拟合后的尺寸变化常数与试样直径的变化不成正比。显微硬度、抗拉强度、延伸率均随着变形量的增加而增大。在单轴拉伸过程中，金包银复合键合丝组分之间相互制约，使单向拉应变变为复杂的二维应力状态，交替变化的应力状态可抑制裂纹的形核，提高材料的塑性和韧性。

关键词：层状复合材料；金包银键合丝；组织演变；变形行为

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