Mechanical Properties Test and Simulation Analysis of Glass Coated Amorphous Filaments

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Abstract. Taking the Co_{68.7}Fe_{4}Ni_{1}B_{13}Si_{11}Mo_{2.3} glass-coated amorphous microwire as the research object, the mechanical properties of the amorphous wire were tested through biaxial tensile experiments, and the fracture deformation process of the amorphous wire was analyzed. Based on the experimental data, the finite element method was used The simulation software ABAQUS numerically simulates the tensile deformation of the amorphous wire, and the fracture relationship between the glass cladding layer and the core wire, and further reveals the tensile deformation fracture behavior of the amorphous wire was analyzed. The experimental results indicate that the fabricated microwires exhibit good tensile properties, and the maximum tensile breaking strength can reach 2918MPa; the fracture of the amorphous wire is a typical brittle fracture, and there is no obvious yield phenomenon. The tensile mechanics simulation results of the amorphous wire are consistent with the experimental results. The glass cladding layer breaks before the core wire, and the stress transfer effect in the amorphous wire is good. The model fracture is consistent with the fracture morphology of the amorphous wire. These results show that the amorphous wire exhibits good tensile properties and stress transmission capabilities, confirming the huge application potential of amorphous wire materials in sensor applications and functional composite materials.

1. Introduction

Amorphous wire material has attracted great interest due to its potential use in a series of scientific research and engineering applications. It has many excellent electromagnetic properties such as giant magnetic impedance, magnetic bistability, microwave absorption, electromagnetic interference shielding, etc. [1-3], has been widely used in a variety of sensors and electronic devices [4-6], as well as functional composite materials [7-8]. The microstructure and magnetic properties of these amorphous wires can be adjusted by annealing and mechanical processing during or after the manufacturing process [9-11], and they can also achieve giant magnetic impedance under the action of Giant magneto-impedance (GMI) effect is significantly improved [12]. However, the potential engineering application value of ferromagnetic amorphous wire not only depends on its excellent magnetic properties, but also closely related to its excellent mechanical properties. Its high strength, high toughness, and high wear resistance make it maintain during the application process. In order to understand the structural strength integrity of other materials, we need to understand its basic mechanical properties and change laws in practical applications, and use these laws to analyze the application of amorphous wires in sensors, functional composite materials and other aspects in combination with their electromagnetic properties. Therefore, mechanical research on this kind of amorphous microwires is essential to enhance their magnetic properties and solve the problems related to their applications in sensors and other aspects. Most of the previous research mainly focused on the tensile strength of amorphous wire
This is due to the small size of the amorphous wire and the rapid fracture process. It is difficult to observe the tensile strength of the amorphous wire during the experiment. The specific fracture process of the amorphous wire can only be analyzed simply through experimental data. The stress transfer process when the amorphous wire is subjected to a tensile force and the fracture relationship between the glass coating layer and the core wire have not been fully studied. In this paper, the mechanical parameters of these CoFe-based amorphous wires during biaxial tensile deformation are measured through biaxial tensile experiments. The deformation process is revealed on the basis of theoretical analysis, and the tensile deformation behavior is further carried out by finite element software. Numerical simulation reveals the stress transfer process of the amorphous wire when subjected to tensile force, and the breaking sequence of the glass cladding layer and the core wire, which is the application of the amorphous wire in force sensors, magnetic sensors and their functional composite materials. The research provides the theoretical basis and simulation basis.

2. Mechanical Properties Test of Amorphous Filaments

2.1. Experimental Materials

The composition of Co-based amorphous wire studied in this paper is: Co_{68.7}Fe_{14}Ni_{1}B_{13}Si_{11}Mo_{2.3}, The microwire has a core-shell structure with uniform thickness and a smooth surface. The total diameter of the microwire is \( D = 27 \mu m \), and the diameter of the metal core layer is \( d = 22 \mu m \).

2.2. Experimental Scheme

Cut 10 wires from the same batch of amorphous wires, make tensile samples according to the international standard ASTM D3379-75, install the cut 10 wires on the fixture as shown in Figure 1, and place the microwires in the middle of the hollow rectangular cardboard, both ends are fixed with tape, and then a layer of cardboard is covered on both ends and bonded with adhesive glue. In the mechanical performance test, the samples prepared above are clamped and cut off the cardboard on both sides, and the test is carried out according to the set loading rate. The tensile test was carried out on the single-fiber strength machine LLY-06ED material testing machine. The maximum tensile force is set to 200cN (i.e. 1.96N, 1N = 10^2cN), and a high-precision sensor is used to measure and analyze the tensile process. The tensile rate is 1mm/min (i.e. 16.667 \( \mu m/s \)), and the amorphous wire is stretched to break.

![Figure 1. Schematic diagram of stretched sample](image)

2.3. Experimental Results and Analysis

The maximum fracture strength of the 10 samples ranged from 1609 MPa to 2918 MPa, the average maximum fracture strength was \( \sigma_{b_{\text{max}}} = 2043 \text{MPa} \), and the average maximum strain was about 2.1%. Calculate the average value of the measured data and draw the average stress-strain curve of the amorphous filaments, as shown in Figure 2. It can be clearly seen that the fracture of amorphous filaments is typical brittle fracture without obvious plastic strain. Samples in the elongation rate is about 1.2% when suddenly there was a obvious stress reduce the drop zone, namely the red box circle.
part of the figure, analysis think this is because there is such a large glass of brittleness and extension rate is small, so when the glass layer in the event of rupture, which is associated with crack in glass layer spread rapidly, resulting in glass layer broke off and failure. After the failure of the glass coating, the core does not fracture, and the core continues to be stressed until the second fracture occurs. The slope of the curve during the second fracture can be approximately regarded as the elastic modulus of the alloy core material.

Figure 2. Tensile stress-strain curve of glass-coated amorphous wire

3. Numerical Simulation

3.1. Parameter Setting and Condition Definition

3.1.1. Geometric parameter and material property setting. The structure diagram of the finite element simulation model of amorphous wire mechanics is shown in Figure.3. It consists of two parts: a metal core layer and a glass cladding layer. The diameter of the amorphous wire core layer is \( d = 22 \mu m \), and the diameter of the glass cladding layer is \( D = 27 \mu m \). The length is \( L = 500 \mu m \). The stress-strain data in the parameter attribute setting of the core material adopts the amorphous wire mechanical property test data in section 2.3, See Table 1 for details. the cladding material is SiO2, the elastic modulus is 20GPa, and the parameter setting refers to the literature [16]. In the finite element simulation, the clamping length of the two ends of the amorphous wire is ignored, and the stress is directly applied to the two ends to perform the finite element simulation.

Figure 3. Schematic diagram of amorphous wire structure
### Table 1. stress-strain parameters of core material

| Stress (MPa) | Strain (%) | Stress (MPa) | Strain (%) |
|-------------|------------|--------------|------------|
| 859.28      | 0.7083     | 1789.86      | 1.6667     |
| 1121.37     | 0.9167     | 1926.36      | 1.8333     |
| 1354.42     | 1.1250     | 2006.85      | 1.9583     |
| 1500.63     | 1.2917     | 2043.39      | 2.1000     |

3.1.2. Model Meshing and Load Definition. When meshing, taking into account the different fracture characteristics of the core layer and the cladding layer, the core layer is meshed. The inner and outer layers are scanned using the hexahedral advanced algorithm, and the unit type is set to eight. The nodal linear hexahedral element reduces the integral (C3D8R), as shown in Figure 4. Load the displacement load at both ends during load definition. The maximum displacement is set to 16 μm, the load is loaded at a uniform speed, and the set tensile rate is 16.667 μm/s (i.e. 1 mm/min), which is the same as the parameters of the tensile test. Be consistent.

![Figure 4. Finite element model of amorphous wire](image)

3.1.3. Boundary Conditions and Definition of Contact Relationship. The boundary conditions, coordinate definitions and axis constraints are shown in Figure 4. Both ends of the amorphous wire are fully constrained by the X and Y axes, and are only allowed to move in the Z direction to apply displacement loads. Because the contact between the cladding layer and the core layer is more complicated, in this study, the interface effect of the interaction between the inner and outer layers of the amorphous wire is not considered for the time being. It is assumed that the inner and outer layers of the amorphous wire are in hard contact. The surface-to-surface contact type is adopted. Considering the strength between the interfaces, the contact coefficient is set to be larger.

3.2. Finite Element Simulation Examples and Analysis

When loading, the tensile stress is transferred from the two ends of the amorphous wire to the middle of the amorphous wire. At this time, the glass coating layer of the amorphous wire and the core wire are subjected to the same tensile force. When the tensile stress reaches 1324 MPa, the coating layer has already occurred. Fracture, as shown in Figure 5(a), at this time the core layer has not yet been significantly broken. Before the glass coating layer is broken, the core wire has been subjected to a considerable load. As the displacement load increases, the coating layer is completely broken. When the glass coating layer is broken, the load continues to act on the core wire. When the stress reaches 1647 MPa, the core layer begins to crack initially. With the increase of displacement load, when the stress reaches the limit close to the average maximum tensile strength σ\(_{\text{bmax}}\) of the amorphous wire, the core layer is completely broken, and finally the amorphous wire breaks and separates. As shown in Figure 5(b). The fracture morphology of the amorphous wire after tensile fracture is shown in Figure 5(c). According to the simulation results, it can be seen that the fracture morphology of the amorphous
wire is not completely flat. This result is consistent with the literature [17-19]. The fracture morphology of the amorphous wire in the literature basically coincides, indicating that the established simulation model has a certain validity.

![Fracture sign of glass coating](image1)

![Cross-section diagram of core fracture process](image2)

![Fracture morphology characteristics](image3)

Figure 5. Mechanical simulation results of amorphous filaments

### 4. Results and Discussion

The tensile deformation fracture behavior of glass-coated Co$_{68.7}$Fe$_4$Ni$_{13}$B$_{11}$Si$_{11}$Mo$_{2.3}$ amorphous microwires was systematically studied and analyzed by experimental research and numerical simulation. The conclusions are as follows:

(1) The experimental results show that the tensile fracture behavior of the amorphous wire is elastic deformation, almost no plastic strain, its maximum fracture strength is distributed between 1609MPa and 2918MPa, and the average fracture strength is 2043MPa, showing good mechanical properties.

(2) A simulation model of the tensile mechanics of amorphous wire was established, and the specific fracture deformation behavior and stress transmission process of the amorphous wire under biaxial tension were simulated. It was found that the glass coating layer of the amorphous wire was earlier than the core wire. The fracture is consistent with the experimental results, and the stress transfer effect in the amorphous wire is good.

Good mechanical properties and stress transfer ability are necessary conditions for the application of amorphous wire to sensors and functional composite materials. The conclusions obtained in this article have not only confirmed the huge application potential of amorphous wire in sensor applications and functional composite materials, but also it provides a theoretical basis and simulation basis for the...
research and development of the application of amorphous wire and its functional composite materials in mechanics.

References

[1] J. Liu, Z. Li, H. Shen, etal. Composite electroplating to enhance the GMI output stability of melt-extracted wires, Mater Design 96 (2016) 251–256.

[2] E. Golubeva, S. Volchkov, S.V. Shcherbinin, etal. Magnetic and micro-wave properties of carbon-coated Co-and Fe-based amorphous wires, IEEE Magn. Lett. 9 (2018) 1–5.

[3] Mustafa, G., Islam, M. U., Zhang, W., etal. Investigation of structural and magnetic properties of Ce3+-substituted nanosized Co-Cr ferrites for a variety of applications[J]. Journal of Alloys and Compounds, 2015, 618: 428–436.

[4] Z. Yang, A. A. Chlenova, E. V. Golubeva, etal. Agnetoimpedance effect in the ribbon-based patterned soft ferromagnetic meander-shaped elements for sensor application, Sensors 19 (2019) 2468

[5] J. Zhang, L. Hao, F. Yang, etal. Biomimic hairy skin tactile sensor based on ferromagnetic microwires, ACS Appl. Mater. Interfaces 8(2016) 33848–33855

[6] Herrero-Gómez C, Aragón A M, Hernandez-Rydings M, etal. Stress and field contactless sensor based on the scattering of electromagnetic waves by a single ferromagnetic microwire[J]. Applied physics letters, 2014, 105(9): 092405.

[7] F.X Qin, H.X Peng, V.V Popov, etal. Giant magneto-impedance and stress-impedance effects of microwire composites for sensing applications. Solid State communications, 2011 (151):293-296.

[8] Alexandra Allue, Paula Corte-León, Koldo Gondra. Smart composites with embedded magnetic microwire inclusions allowing non-contact stresses and temperature monitoring[J]. Composites Part A,120(2019)12–20.

[9] Y.Y. Zhao, H.Y. Hao, and Y. Zhang, Preparation and giant magneto-impedance behavior of Co-based amorphous wires, Intermetallics, 42(2013), p. 62.

[10] H. Wang, F.X. Qin, D.W. Xing, etal. Relating residual stress and microstructure to mechanical and giant magneto-impedance properties in cold-drawn Co-based amorphous microwires, Acta. Mater., 60(2012), No. 15, p. 5425.

[11] Y.J. Zhao, X.F. Zheng, F.X. Qin, etal. A self-sensing microwire/epoxy composite optimized by dual interfaces and periodical structural integrity[J]. Composites Part B,2020,182.

[12] S.L. Zhang, J.F. Sun, D.W. Xing, etal. Large GMI effect in Co-rich amorphous wire by tensile stress, J. Magn. Magn. Mater., 323(2011), No. 23, p. 3018.

[13] Sun H C, Ning Z L, Wang G. Tensile Strength Reliability Analysis of Cua8Zr18Al4 Amorphous Microwires[J]. Metals, 2016, 6:296-305.

[14] Wang H, Xing D W, Peng H X, etal. Nanocrystallization Enabled Tensile Ductility of Co-based Amorphous Microwires [J]. Scripta Materialia, 2012, 66: 1041–1044.

[15] Yi J, Wang W H, Lewandowski J J. Sample Size and Preparation Effects on the Tensile Ductility of Pd-based Metallic Glass Nanowires[J]. Acta Materialia, 2015,87: 1–7.

[16] ZHANG J. Research on Preparation and Sensitive Properties of Ferromagnetic Amorphous Filaments Composites [D]. Harbin Institute of Technology,2017.

[17] Shen, H., Liu, J., Wang, H., etal. Optimization of mechanical and giant magneto-impedance (GMI) properties of melt-extracted Co-rich amorphous microwires [J]. Physical Status Solidi (a), 2014, 211(7): 1668–1673.

[18] Xiao, W., Huan, W., Hong, S., etal. Tensile properties and fracture reliability of a glass-coated Co-based amorphous microwire [J]. International Journal of Minerals, Metallurgy and Materials, 2014, 21(6): 583-588.