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Research Article

Stress-Strain Characteristics and Electrical Conductivity of Niobium Nanopowder modified Silicon Bronze

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Abstract

Understanding the response of materials to various loads is crucial for fabricating resilient components capable of withstanding anticipated stresses. This experimental study addresses the limited information on the tensile behavior of silicon bronze by investigating the stress-strain characteristics of Cu-4wt%Si alloys modified with niobium nanopowder. The surface morphology of the fabricated alloys was analyzed using a Scanning Electron Microscope (SEM). SEM analysis of the Cu-4wt%Si alloy revealed columnar grains sparsely distributed in the copper matrix, contributing to low strain-to-fracture behavior. Doping the alloy with niobium nanopowder resulted in notable grain modification, increased grain boundary density, and improved grain distribution, correlating with higher strain-to-fracture values. Notably, the Cu-4wt%Si-1.1wt%Nb alloy exhibited significant changes in percentage elongation, ultimate tensile strength, yield strength, fracture strength, and tensile toughness. Furthermore, niobium nanopowder additions increase the hardness and electrical conductivity values, peaking at 305 HV and 54.9 %IACS with 1.1 wt% Nb.

Introduction

The stress-strain characteristics of materials remain crucial in the design of engineering materials for various applications. They offer valuable insights into materials' response to diverse loads, aiding engineers and researchers in crafting robust components capable of withstanding anticipated stresses. Adequate understanding of stress-strain behavior facilitates material selection, prediction of failure points, and the optimization of materials designs for enhanced efficiency and durability across various applications. Copper-based alloys are known for their high strength, superelectrical conductivity, hardness, ductility, and malleability [1-8]. Based on these unique properties, they are found suitable for electrical connectors, fasteners, conduits, valve stems, lead frames, bolts, and electronic signals [9-16]. Silicon bronze refers to copper alloy with a silicon content ranging from 2% to 4wt% [12-14]. It is known for its excellent corrosion and wear resistance, high-temperature stability, weldability, hardness, and aesthetic appeal, hence considered a material for fasteners, bolts, propellers, shafts, claddings, and sculptures [17-20].

Earlier studies have reported the detrimental effect of the dendritic structure of silicon bronze on its mechanical properties and electrical conductivity [21-24]. These anomalies limit the advanced applications of the material in industries where a combination of hardness and strength is paramount. Out recent studies demonstrated the excellent properties of silicon bronze (Cu-3Si) via alloying and cooling techniques [25-27]. From the studies, the modified dendritic grains enhanced the percentage elongation, strength, and hardness [28-33].

Tavolzhanskii, et al. [28] obtained twin grains in Cu-Si-Mn silicon bronze via drawing and adequate annealing treatment. Filippov, et al. [29] developed recrystallized grains with high-angle boundaries in Cu-Si-Mn silicon bronze via pre-deformation and annealing treatment, improving the UTS and strain-to-fracture. Asaolu, et al. [32] achieved a grain modification in Cu-Si alloy through alloying with nickel

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and pre-deformation. Aravind, et al. [33] developed a silicon bronze with improved surface hardness, corrosion, and wear resistance via modification of grain by gas tungsten arc. Well-known high-strength copper alloys include Cu-Ni-Si [36,37], Cu-Ti-Cr [38], Cu-Cr-Nb [39], Cu-Co-Si [40], and Cu-Fe-Cr [41]. Nb enhances the mechanical and electrical properties of these alloys by promoting phase precipitation and stabilization [39].

However, mechanical and electrical properties and stress-strain characteristics of Cu-Si-Nb alloys remain unclear. Therefore, this study aimed to develop a novel Cu-4Si-xNb alloy with improved mechanical and electrical performance by varying the concentrations of niobium nanopowder. Additionally, the study explored the behavior of Cu-Si-Nb alloys at different stress levels and failure points in service.

Experimental procedure

Fabrication and testing of Cu-4wt%Si and Cu-4wt%Si-xNb alloys

The study utilized high-purity materials, including 99.99% pure copper rods, 99.5% pure silicon powder, and 99.9% pure niobium nanopowder. The Cu-4wt%Si and Cu-4wt%Si-Nb alloys were fabricated and machined to the appropriate standards for the mechanical and electrical properties tests. The tensile strength, hardness, and electrical conductivity measurements followed established procedures as reported in our previous research works [1,34]. Surface morphology was analyzed using a Carl Zeiss scanning electron microscope (EVO/NA10). Sample preparation involved thorough grinding, polishing, and etching in a solution of iron III chloride, HCl, and water for 30 seconds before analysis.

Results and discussions

Microstructures of niobium nanopowder-modified silicon bronze

Figure 1 depicts the TEM image of the as-received niobium nanopowder (99.9% purity) detailed by Ujah, et al. [35]. The image reveals clustered nanoparticles. Additionally, the particle size distribution is presented in Figure 1b. The particle size distribution, analyzed using ImageJ, provided additional insights into the nanoscale characteristics of the niobium nanopowder.SEM microstructure of the Cu-4wt%Si presented in Figure 2 reveals columnar grains sparsely distributed in the copper matrix. This particular grain morphology may explain the observed low strain-to-fracture behavior at different loads, as demonstrated in Figure 3. SEM images of Cu-4wt%Si doped with various concentrations of niobium nanopowder depict modified grain morphology, with the modification becoming more pronounced with increasing niobium nanopowder concentrations (Figure 2c-e). The SEM of Cu-4wt%Si-1.1wt%Nb alloy reveals substantial grain modification, increased grain count, and improved distribution. These correlate with a higher strain-to-fracture value, as depicted in Figure 3. This comprehensive analysis sheds light on the morphological changes induced by niobium nanopowder doping, providing valuable insights into the alloy's microstructural evolution and its potential impact on mechanical properties.

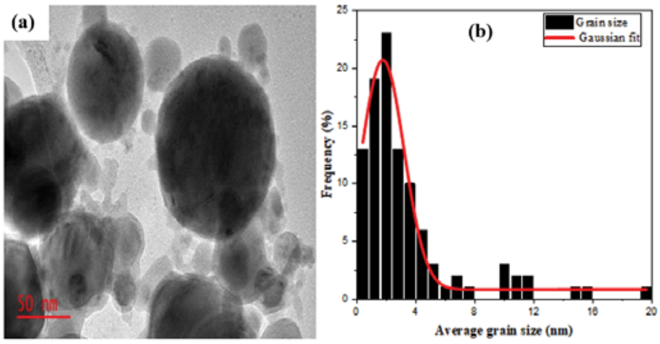

Figure 1: Surface morphology (TEM) and grain distribution of niobium nanopowder.

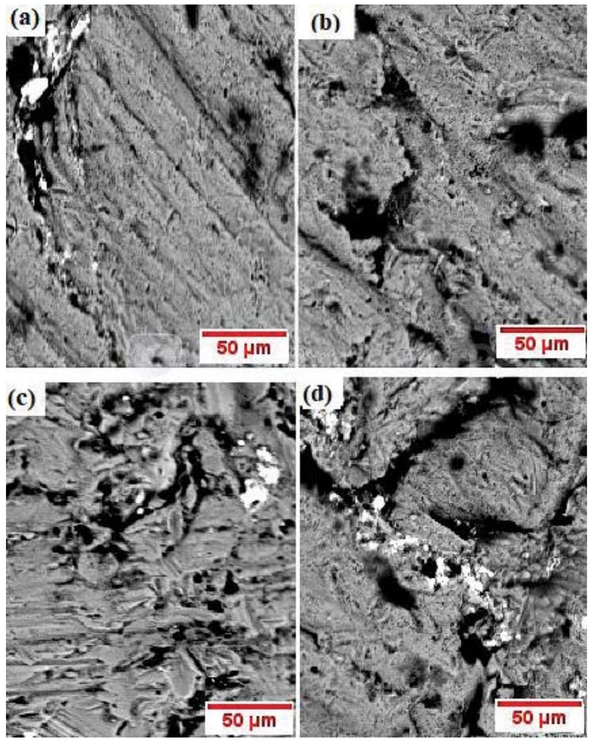

Figure 2: SEM microstructures of (a) Cu-4Si (b) Cu-4Si-0.2Nb (c) Cu-4Si-0.8Nb (d) Cu-4Si-1.1Nb alloys.

Stress-strain behavior and electrical conductivity of niobium nanopowder-modified silicon bronze

Figure 3 illustrates the stress-strain behavior of Cu-4wt%Si and Cu-4wt%Si-xwt%Nb alloys under various loads. The curves provide a detailed insight into how the developed alloys respond to different stresses. Table 1 represents the stress-strain components of the alloys. The Cu-4wt%Si exhibits a notably low stress-to-fracture value, indicating poor ductility. The percentage elongation, ultimate tensile strength, yield strength, fracture strength, and tensile toughness reached 7.3%, 55 MPa, 26 MPa, 6.10 MPa, and 61.1 J/m^3, respectively. Cu-4wt%Si alloy doped with various concentrations of niobium nanopowder demonstrates improved strain-to-fracture behavior. The strain-to-fracture value increases with higher niobium nanopowder concentrations, with Cu-4wt%Si-1.1wt%Nb alloy exhibiting significant enhancements. This alloy records percentage elongation, ultimate tensile strength, yield strength, fracture strength, and tensile toughness values

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of 54.7%, 274 MPa, 205 MPa, 171 MPa, and 22,500.4 J/m³, respectively. These improvements can be attributed to the intense modification of grain structure induced by the addition of niobium nanopowder, (Figure 2). Figure 4 presents the hardness and electrical conductivity (EC) values of Cu-4wt%Si and Cu-4wt%Si-wt%Nb alloys. Cu-4wt%Si alloy exhibited hardness and EC values of 206 HV and 43.2% IACS. After incorporating niobium nanopowder, the hardness and electrical conductivity were increased by 8.3% and 14.8%, respectively. The hardness and EC values showed increasing trends with niobium nanopowder additions, reaching 305 HV and 54.9% IACS, respectively, resulting from grain modification and increased precipitation of intermetallic compounds. Cu-Si-Nb alloys could serve in components of biomedical devices that require reliable electrical conductivity and mechanical strength, such as pacemakers or other implanted electronic devices.

Future directions

Future research should focus on additive manufacturing and optimize metallurgical processes to develop Cu-Si-Nb alloys with unique mechanical and electrical properties. Additionally, the alloy's suitability for biomedical applications, such as surgical instruments, dental tools, and bioelectronic devices, should be investigated, leveraging its strength, durability, and conductivity.

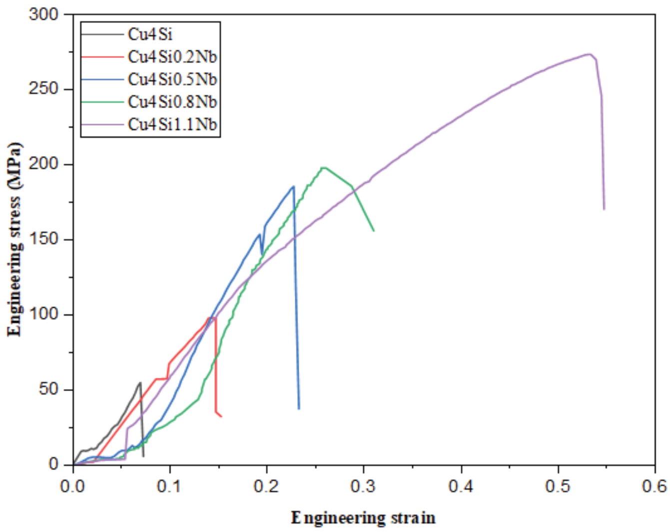

Figure 3: Stress-strain characteristics of (a) Cu-4wt%Si, (b) Cu-4wt%Si-0.2wt%Nb, (c) Cu-4wt%Si-0.5t%Nb, (d) Cu-4wt%Si-0.8wt%Nb, and (e) Cu-4wt%Si-1.1wt%Nb alloys.

Table 1: Stress-strain parameters of niobium nanopowder-modified silicon bronze.

Alloy compositions	Elongation at break (%)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Fracture strength (MPa)	Tensile toughness (J/m³)
Cu-4wt%Si	7.30	55	26	6.10	61.1
Cu-4wt%Si-0.2wt%Nb	15.20	98	57	32.70	484.0
Cu-4wt%Si-0.5wt%Nb	23.30	186	149	32.74	2165.4
Cu-4wt%Si-0.8wt%Nb	30.98	198	164	156.2	5884.0
Cu-4wt%Si-1.1wt%Nb	54.7	274	205	171.0	22500.4

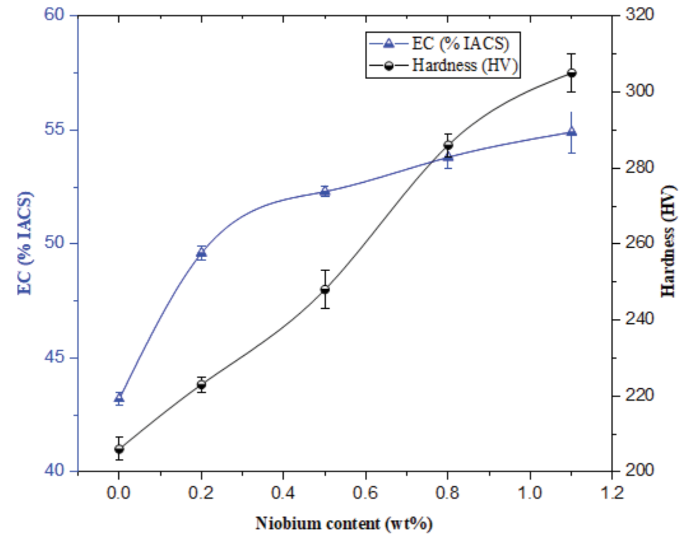

Figure 4: Hardness and electrical conductivity of niobium nanopowder-modified silicon bronze.

Conclusion

The study on niobium nanopowder-modified silicon bronze revealed significant improvements in the microstructure and properties of Cu-4wt%Si alloys. The addition of niobium nanopowder notably altered the grain morphology, leading to high strain-to-fracture values. The niobium-doped Cu-4wt%Si alloy demonstrated improved elongation at break, tensile strength, yield strength, fracture strength, and tensile toughness. The hardness and electrical conductivity reached maximum values of 305 HV and 54.9% IACS, respectively. These findings offer valuable insights for the development and application of advanced materials.

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