COMPARATIVE ANALYSIS OF CU-NB MICROCOMPOSITE CONDUCTOR WELDING TECHNIQUES

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Abstract

This study investigates the microstructure and thermal performance of Cu-Nb microcomposite conductors welded using various techniques, including thermite welding, laser welding, electron beam welding, and pressure welding with a strong magnetic field. The goal was to assess how different welding methods impact the microstructure and temperature distribution of the welded joints. Temperature distribution across all welding methods met the standards for electrical contact joints, ensuring reliable performance. Cu-Nb microcomposite conductors, with their exceptional strength and conductivity, are highly suitable for high-performance magnetic field applications. The findings provide valuable insights for optimizing welding processes, contributing to advancements in welding technology and material science.

Keywords: Cu-Nb Microcomposite Conductors, Welding Techniques, Electrical Contact Joints

1. INTRODUCTION

Nanostructured materials exhibiting excellent electrical and thermal conductivity along with high mechanical strength are essential for winding wires used in manufacturing high-field magnets. Cu-Nb composites are potential candidates for producing electrical transformers, powerful electromagnets for metal handling, and equipment for plastic deformation via magnetic fields [1].

Magnetic fields stronger than $\mu 0H=45$ T can be produced as short, irregular pulses. Magnetic flux compression can achieve up to B=2800T, but such conditions typically destroy the magnet after a single pulse. Current research aims to develop resilient magnets capable of generating a magnetic flux of B=100T for 10 ms. High tensile strength is needed to withstand the Lorentz force, and high electrical conductivity is required to minimize Joule heating caused by intense magnetic currents. One critical unresolved issue in strong magnetic field technology is creating reliable welded connections for high-strength microcomposite conductors. This might be theoretically addressed using specialized welding techniques. The mutual solubility of Cu and Nb in the solid state is minimal. Post-crystallization, Cu-Nb alloys consist of two distinct metallic phases [2]. During plastic deformation, the diameter and spacing between Nb dendrites significantly decrease, creating a beneficial band microstructure and enhancing the alloy's mechanical properties. Concurrently, the high electrical conductivity of the copper phase remains unaffected.

The high melting point of niobium and their very low mutual solubility pose challenges in the welding of Cu-Nb wires. One method involves melting and casting in a vacuum furnace, followed by multiple drawing and annealing processes. Another method uses iterative repetition where wires from Cu-Nb microcomposites are inserted into a copper tube at each stage. Cu-Nb alloys can also be melted in an arc or electron-beam furnace, and the resulting billet processed. Annealing can lead to spheroidization and growth of niobium fibers, significantly affecting mechanical and magnetic properties. Alternatively, mechanical alloying of powders followed by plastic working and heat treatment can produce Cu-Nb microcomposites, with powder metallurgy methods substituting metallic niobium with niobium carbide. Solid-state welding can effectively eliminate or significantly reduce many issues faced in fusion welding. This is because it operates at lower temperatures, avoiding problems like transformations, solidification stresses, and cracking caused by melting. It also prevents reactions with the environment, phase interactions, and softening due to structural changes [3].

This paper investigates the microstructure of Cu-Nb microcomposite conductors and the temperature difference between the joint and the conductor in Cu-Nb microcomposite conductors that were welded using various techniques. The main aim of the study is to determine the influence of Cu-Nb conductor welding methods on the microstructure and temperature difference between the obtained welded joints.

2. MATERIALS AND METHODS

2.1 Structure, properties and applications of Cu-Nb microcomposite conductors

Selecting an appropriate conductor for a specific magnet design hinges on the characteristics of the magnetic field to be generated. Two pivotal properties of conductors used in magnetic field inductors are their strength and conductivity. Prior to 1980, only copper conductors were employed for winding inductors. While copper is an excellent thermal and electrical conductor, it lacks the mechanical strength necessary to withstand the Lorentz forces exerted by the magnetic field on the inductor windings. A substantial breakthrough in this field was achieved with the advent of metal composite conductors. Materials used for the windings of solenoids that generate magnetic fields with intensities between 5 and 100 T must exhibit high strength (exceeding 750 MPa) and superior electrical conductivity (above 60-70% IACS). High strength is essential to resist the enormous Lorentz forces, while excellent electrical conductivity is crucial to minimize heating caused by substantial current flow. Furthermore, these materials must possess sufficient ductility to prevent fracturing or cracking during the winding process. Presently, four types of composite conductors are predominantly used in pulsed magnetic inductors: Cu-Nb, Cu-Ag, GlidCop microcomposites, and CuSS macrocomposites. Among these, Cu-Nb microcomposites stand out as the most effective conductors, offering exceptional strength and conductivity. Their strength ranges from 1100-1500 MPa (in contrast to 270 MPa for standard copper conductors), with a yield strength of 850 MPa and electrical conductivity of 67-70% IACS. The structure of Cu-Nb microcomposite conductors comprises a copper matrix embedded with exceedingly fine niobium fibers. These Nb fibers fortify the copper matrix, imparting greater conductor strength without obstructing electron flow, thus facilitating efficient electrical current transmission.

2.2 Thermite welding

The thermite welding utilized a Cu-Nb microcomposite conductor with a composition of 82% copper and 18% niobium, and diameters ranging from 2.4 to 4.2 mm. For the experiments, a thermal mixture was selected to ensure a high reaction temperature between 2449°C and 2469°C, resulting in up to 85% copper yield and at least 15% slag by mass, with a molar ratio of Al to CaSi2 of 2:1.

2.3 Laser welding

The laser welding utilized a Cu-Nb microcomposite conductor composed of 82% copper and 18% niobium, with a cross-sectional area ranging from 1.7 to 0.8 mm². For laser welding of the microcomposite conductors with filler metal, welding wire grade 2.1006 (CuSn1) with a diameter of 0.3 mm was used. This filler metal offers superior mechanical strength compared to pure copper conductors.

2.4 Electron beam welding

The electron beam welding utilized a Cu-Nb microcomposite conductor composed of 82% copper and 18% niobium, with cross-sectional dimensions ranging from 2.4 to 4.2 mm. The welding of these copper-niobium microcomposite conductors was performed using advanced low-voltage electron beam welding equipment, comprising an H<A-15 power unit and an AB 400 diffusion pump.

2.5 Pressure welding with a strong magnetic field

The pressure welding with a strong magnetic field utilized Cu-Nb microcomposite conductors with dimensions ranging from 2.4 to 4.2 mm. To create a press fit connection, a sleeve made of pure technical copper was used, matching the chemical composition of the copper sheath of the microcomposite conductor. Magnetic pressing of the Cu-Nb conductors was carried out using an experimental pulsed system, which included a high-voltage discharge unit capable of delivering pulses up to 6.8 kJ and a sample inductor.

2.6 Diffusion welding with interlayer

The diffusion welding with interlayer (0.1 mm thickness foils from pure Cu and Ti) utilized Cu-Nb microcomposite conductors with dimensions ranging from 2.4 to 4.2 mm. Welding of the Cu-Nb conductors was carried out using a diffusion welding system ION-3 and Ar inert shielding gas. Welding parameters: temperature 885° C, pressure 5 MPa, time 1 min.

2.7 Flash welding

The flash welding utilized Cu-Nb microcomposite conductors with dimensions ranging from 2.4 to 4.2 mm. Flash welding of the Cu-Nb conductors was carried out using a flash welding machine MKCCO. Welding parameters: current 2700A, flashing time 0.5 s, upsetting force 500 N, total allowance 1,6 mm.

2.8 Analysis methodology

Microscopic and macroscopic examination of the welds was conducted according to EN ISO 17639 and EN 60512-1-1 standards. The joint structures were analyzed after polishing and etching. The microstructure of the weld and the transition zone was investigated using optical microscopy (up to 1500x magnification) with a Nikon Eclipse MA200 metallographic microscope, equipped with an integrated video camera and software suite for image processing. FLIRE49001 Infrared Camera was used for temperature measuring in the join during heating by electric current (according EN 60512, MIL-STD 1344A, MIL-STD 202G, EIA-364, GOST 17441, GOST 10434).

3. RESEARCH RESULTS

3.1 Thermite welding

The thermite weld joint had a cross-sectional area of approximately 100 mm^2. No unacceptable macrodefects (such as cracks, pores, or inclusions) were found in the cross-section of the weld (**Figure 1a**). The thermal reaction yielded about 76% copper and 24% slag. It was confirmed that the thermal reaction produces an amorphous-crystalline slag (anorthite) with a melting point of 1550°C.

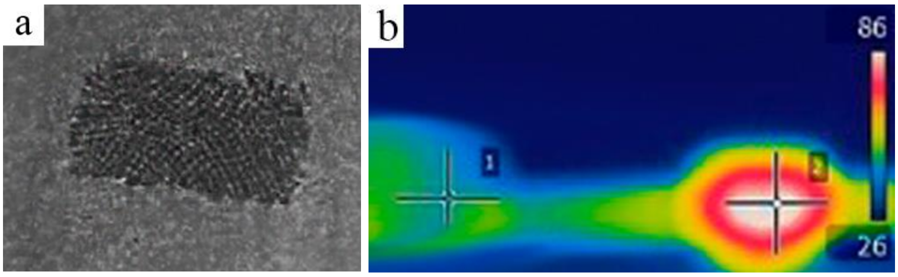

Figure 1 Thermite welding Cu-Nb wire: (a) cross-section; (b) temperature distribution in the thermite welded joint after 2 min of heating.

The microstructure of the conductor is surrounded by a copper alloy, which crystallized from the molten state due to an exothermic thermal reaction. Examination of the thermal joint's cross-section reveals that the Cu-Nb conductor itself did not melt. Its shape and microstructure remained virtually unchanged, indicating that the conductors were joined at an exceptionally high welding speed (**Figure 1b**). Heating test results demonstrated that the temperature distribution, as recorded by a thermal imager, meets the standards required for electrical contact joints

3.2 Laser welding

The overall appearance of the laser-welded joints with filler metal is shown in (**Figure 2**). The cross-sections of these welds (**Figure 2a**) demonstrate that laser welding, both with and without filler material, produces high-quality joints free from unacceptable internal defects (such as cracks, fusion defects, incomplete fusion, porosity, inclusions, and other critical discontinuities). The weld seam width is approximately 3.0 mm without filler metal and about 1.8 mm with filler metal. In the latter case, the narrower weld width and smaller cross-sectional area result from some of the welding energy being consumed to melt the added metal. When welding without filler metal, the weld joint exhibits a more homogeneous microstructure and chemical composition across the entire cross-section. The microstructure of the transition zone comprises two phases: a Cu matrix and a dispersed Nb phase. During laser welding, the vigorous mixing in the weld pool leads to a uniform distribution of Nb particles within the copper matrix. The heating test results (**Figure 2b**) indicated that the temperature distribution, as recorded by a thermal imaging camera, meets the requirements for electrical contact joints.

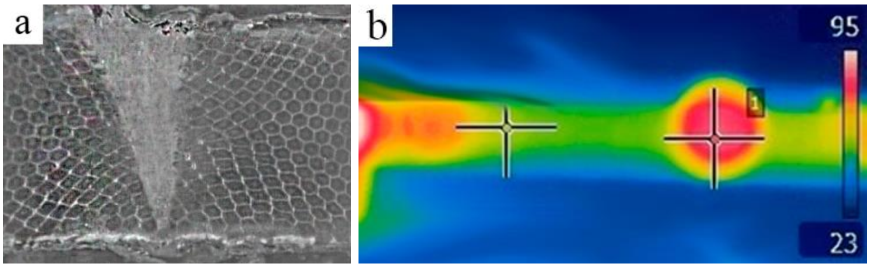

Figure 2 Laser welding of Cu-Nb wire: (a) laser penetration depth after welding on one side; (b) temperature distribution in the laser welded joint after 2 min 60 A current flow.

3.3 Electron beam welding

Electron beam welding of Cu-Nb microcomposite conductors was conducted using varying beam spot sizes and power densities. When a high-power density electron beam was applied, the welding pool vaporized, resulting in the Cu-Nb microcomposite conductor being cut instead of melted and welded. Microscopic examination of the longitudinal section (**Figure 3a**) revealed that the resulting weld joints were free from unacceptable welding defects. The phase diagram for the Cu-Nb binary system indicates that copper and niobium have very limited mutual solubility. The structure of the electrode-less weld consists of a copper matrix with niobium dendrites. This microstructure is similar to that of a Cu-Nb alloy (82 wt.% Cu and 18 wt.% Nb) obtained from a melting furnace. However, the microstructure achieved by welding with an electric wire surpasses other welding methods because the welding occurs in a vacuum, which helps to avoid most welding defects. Heating tests on samples with electrically welded joints showed that the temperature distribution, recorded by a thermal imager, meets the standards required for electrical contact joints (**Figure 3b**). The temperature difference between the joint and the conductor when an electric current flow does not exceed the allowable temperature difference.

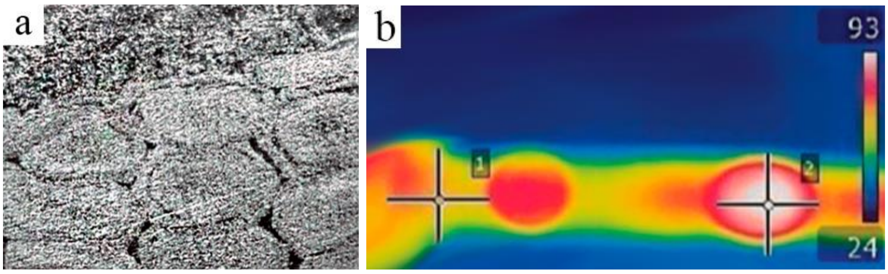

Figure 3 Electron beam welding of Cu-Nb wire: (a) cross section of joint; (b) temperature distribution in the welded joint after 2 min of heating.

3.4 Pressure welding with a strong magnetic field

Cu-Nb microcomposite conductor joints were created using the method of pressing a copper sleeve in a pulsed magnetic field. The cross-sectional photographs of the joints (**Figure 4a**) show that the copper sleeve is tightly pressed against the Cu-Nb conductor, with their surfaces seamlessly bonded over the entire contact area. This forms an indestructible welded joint. Heating tests on samples with these welded joints, conducted using an electric current, demonstrated that the temperature distribution recorded by the thermal imager met the standards for electrical contact joints (**Figure 4b**). The temperature difference did not exceed the permissible limits

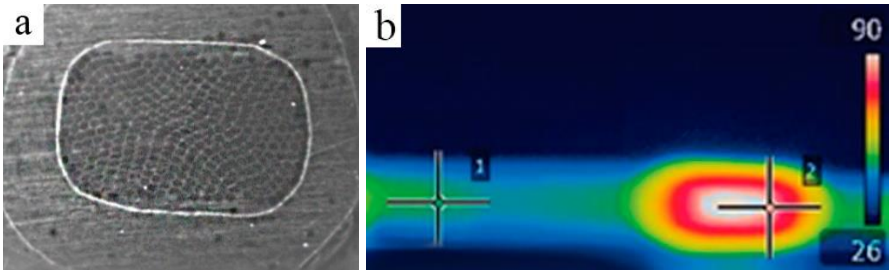

Figure 4 Pressure welding of Cu-Nb wire: (a) cross-section structure of the joint; (b) temperature distribution in the welded joint after 2 min of heating.

3.5 Diffusion welding with interlayer

Cu-Nb microcomposite conductor joints were created using the method of solid-state diffusion welding with interlayer (using Cu and Ti foils). The cross-sectional photographs of the joints (**Figure 5a**) show that Cu-Ti interlayer helps to improve the contact state of the material surface, lower the preparation requirements for the welding surface, reduce the diffusion welding temperature and pressure, shorten the diffusion welding time, and avoid the tendency to form brittle intermetallic phases, as well as other metallurgical problems. Heating tests on samples with these welded joints, conducted using an electric current, demonstrated that the temperature distribution recorded by the thermal imager met the standards for electrical contact joints (**Figure 5b**).

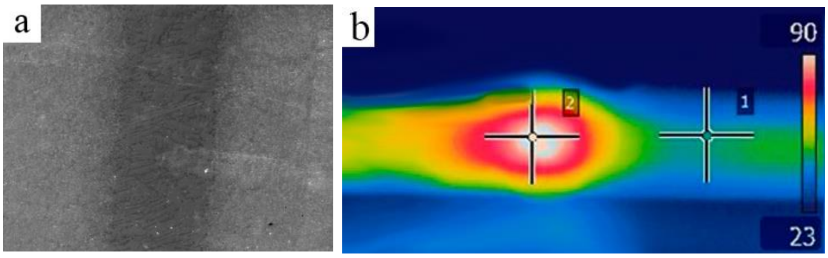

Figure 5 Diffusion welding of Cu-Nb wire: (a) cross-section structure of the joint welded with interlayer; (b) temperature distribution in the welded joint after 2 min of heating.

3.6 Flash welding

Cu-Nb microcomposite conductor joints were created using the flash welding method. The cross-sectional photographs of the joints (**Figure 6a**) show that weld joints were formed by flash welding without lack of penetration, cracks, large misalignment or other discontinuity at the interface. The bonding line and edges of the Cu-Nb wire can be clearly identified from the view; however, the edges were joined completely and the welded joint was formed without any unacceptable discontinuities. The heating test results (**Figure 6b**) indicated that the temperature distribution, as recorded by a thermal imaging camera, meets the requirements for electrical contact joints.

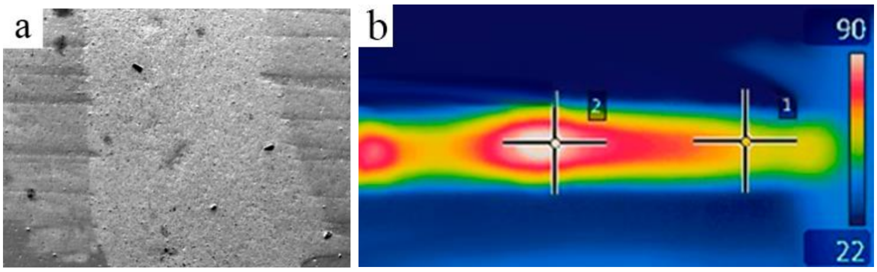

Figure 6 Flash welding of Cu-Nb wire: (a) cross-section structure of the joint; (b) temperature distribution in the welded joint after 3 min of 200 A current flow.

4. CONCLUSION

This study analyzed the microstructure and thermal performance of Cu-Nb microcomposite conductors welded using thermite, laser, electron beam, pressure, solid-state diffusion and flash welding techniques. All methods produced high-quality, defect-free joints. The temperature distributions recorded by thermal imaging met the standards for electrical contact joints, ensuring reliable performance. Cu-Nb microcomposite conductors are highly suitable for high-performance magnetic field applications, offering exceptional strength and conductivity.

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