INVESTIGATION OF THE WELDING PROCESS AND JOINT PROPERTIES IN A Cu-Nb 18% MICROCOMPOSITE CONDUCTOR PRODUCED BY THE RESISTANCE WELDING METHOD

Paulius BEINORAS, Nikolaj VIŠNIAKOV, Oleksandr KAPUSTINSKYI

Vilnius Gediminas Technical University, Vilnius, Lithuania, EU, paulius.beinoras@vilniustech.lt

https://doi.org/10.37904/metal.2025.5093

Abstract

The strong magnetic field systems are widely used in modern fundamental and applied research, as well as in the most advanced industrial processes. These systems generate magnetic fields ranging from 5 to 100 Tesla, which can expose conductors due to extremely high Lorentz forces. Consequently, the conductor materials must exhibit exceptional mechanical strength (with an ultimate tensile strength of at least 600 MPa) and good specific electrical conductivity (IACS ≥ 60%). Traditional conductors such as copper, aluminum, gold, and silver are unable to withstand these large stresses. Therefore, micro-composite materials of conductors have been developed, combining high strength with favorable electrical conductivity. One of the key unresolved challenges in high-field magnetic systems is the development of reliable non-destructive joints and their joining technologies. In practice, the majority of conductor joints are still made using mechanical fastening or soldering methods, which are inherently destructive and often lack long-term reliability. This study investigates resistance welding technology and properties of Cu-Nb 18% micro-composite conductor joints. The research focuses on the selection of upset welding parameters, analysis of the chemical composition and microstructure of the butt joints, evaluation of the mechanical and electrical properties of the butt joints.

Keywords: Cu-Nb 18%, micro-composite, resistance welding, ultimate strength, electrical conductivity

1. INTRODUCTION

Magnetic fields are widely applied across various fields of science and industry today. This is a rapidly developing area of research and technology, where pulsed, continuous and eddy current magnetic fields are employed. Strong magnetic fields have become essential tools in scientific investigation due to the unique phenomena they induce, such as levitation, structural changes in materials, phase transitions, superconductivity, and more. Globally recognized projects utilizing strong magnetic field technologies: Large Hadron Collider (LHC) at CERN, Helion Energy's fusion reactors Trenta and Polaris, the International Thermonuclear Experimental Reactor (ITER), the Joint European Torus (JET), as well as other stellarators and tokamaks. Magnetic fields exceeding 45 T can currently be generated in the form of relatively short, irregular pulses. Usually, the magnet is often irreversibly damaged after emitting a single pulse. Ongoing research focuses on the development of durable magnets capable of generating magnetic flux densities up to 100 T for durations of around 10 µs or longer [1].

The intense Lorentz forces induced by strong magnetic fields demand new materials that exhibit both high tensile strength, excellent electrical and thermal conductivity. High strength is required to withstand the mechanical stresses, while good conductivity minimizes Joule heating caused by high current densities. Cu-Nb microcomposites are among the one of most promising materials for use in electrical transformers, solenoids, and other high-performance magnetic applications [2].

One of the major challenges in this area is developing reliable methods to join these microcomposite conductors in a way that preserves their mechanical and electrical properties. Currently, the most commonly used techniques are bolted or soldered joints. However, these assembling methods often fail to provide performance comparable to that of the seamless base material. Although soldered and bolted joints are generally preferred over fusion welding which degrades the microstructure and reduces strength and conductivity. But they are still not ideal for high-reliability applications [3]. An alternative welding method for microcomposite materials such as Cu-Nb is solid-state upset resistance welding being one of the most promising techniques. Because two materials are joined without melting by applying pressure and passing an electric current through their contact surfaces. The heat generated by electrical resistance reduces the yield strength of the material, allowing localized plastic deformation to occur under moderate pressure. This enables solid-state bonding without melting the materials. Typically, the materials are heated to approximately 80% of the melting point of the lower-melting component, while pressure is applied up to the yield strength of the softer material in the pair. This pressure must be sufficient to cause plastic deformation at surface asperities and promote creep, ensuring full contact across the bonding interface. Since no melting occurs, the weld metal retains many characteristics of the multiphase base material. Welds exhibit a hot-worked structure, making them metallurgically closer to the joined material, with minimal disruption of microstructure and phase composition, which does not significantly affect weldability [4]. Welding in solid state can eliminate or minimize most problems encountered with fusion because the temperatures are lower, avoiding phase transformations, solidification stresses, or cracking caused by melting, oxidation reactions, phase interactions or structural softening. The resulting microstructure is notably different, featuring flow patterns rather than the solidification structures typically found in fusion welds [5]. Upset resistance butt welding is a thermomechanical pressure welding method that can be performed with or without metal melting. When the joint is heated only to a plastic state, without fusion, it is referred to as resistance welding, a form of solid-state welding. This welding method offers greater control over both process parameters and weld reliability compared to other techniques. This work aims to investigate resistance welded Cu–Nb 18% conductors. The research includes microstructural analysis of the resitance welded joints, evaluation of their electrical and mechanical properties.

2. MATERIALS AND METHODS

The investigation was carried out on a Cu–Nb 18% microcomposite conductor with dimensions of 4.2 × 2.4 mm, in which the Nb filaments have a diameter of less than 15 nm. The tensile strength (Rm) of this Cu–Nb 18% conductor reaches 1100–1500 MPa, the yield strength (Re) is 850 MPa, the relative elongation (S) is 4.2%, and the electrical conductivity (σ) is approximately 65% IACS. The study focused on fragments of this conductor and its butt-welded joints **(Figure 1)**, which were produced using the upset resistance welding method.

Figure 1 Structure of Cu-Nb 18% microcomposite conductor and welded joint

Prior to resistance welding, the mating surfaces of the Cu-Nb 18% conductor specimens were ground flat using conventional grinding techniques, concluding with 2000-grit waterproof abrasive paper to ensure uniform contact. The surfaces were then polished with 0.5 μm Al_2O_3 powder to achieve a mirror-like finish suitable for welding. Specimens were ultrasonically cleaned in ethanol to remove any residual contaminants and air-dried. The polished surfaces were inspected under a microscope, and their surface roughness was measured using a profilometer, confirming values not exceeding 5 μm. Subsequently, the specimens were carefully aligned and assembled coaxially in the resistance welding machine, as shown in **Figure 2**. Initial welding parameters were determined empirically to define an optimal range capable of generating sufficient heat input to bond the Cu-Nb 18% microcomposite conductor contact surfaces without causing melting or compromising structural integrity. The calculated welding parameters are presented in **Table 1**.

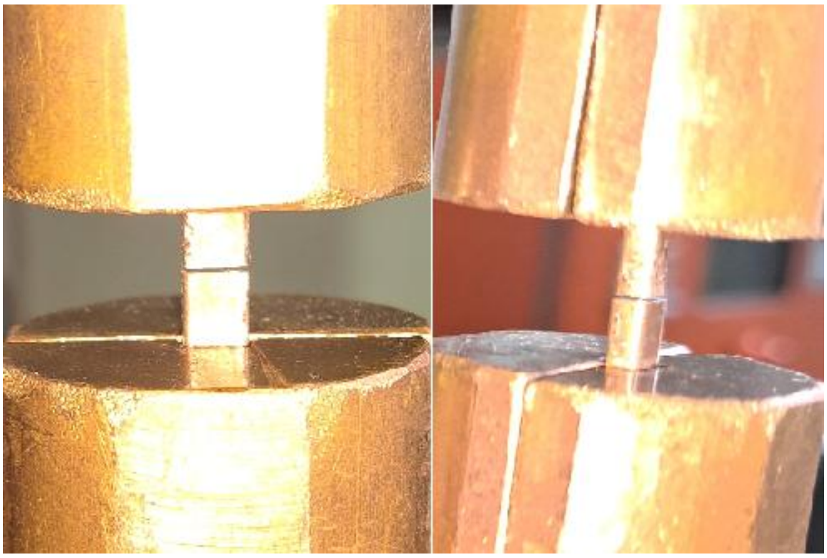

Figure 2 Cu-Nb 18% microcomposite conductor assembly prior to welding

Initial welding parameters were determined empirically to identify the optimal range that generates sufficient heat input to bond the contact surfaces of the Cu-Nb 18% microcomposite conductor without causing melting. The calculated welding parameters are presented in **Table 1**.

Table 1 Calculated upset resistance welding parameters

Welding current (A)	Welding current density (A/mm^2)	Welding force (N)	Upsetting force (N)	Base length (mm)	Upset allowance (mm)	Welding time (s)	Temperature during welding (°C)
2846	285	3500	4300	7	1	0,35	868

The weld zone was shielded with argon inert gas throughout the welding process to prevent oxidation of the contact surfaces. Temperature in the contact area was monitored using a non-contact infrared Optris Infrared Camera PI450i (Optris IR Sensing, LLC, Portsmouth, NH, USA), featuring a measurement range of −20 to +1500 °C and an accuracy of ± 2%. The series of resistance-welded joints were produced, and the welding parameters were selected based on visual inspection and subsequent experimental evaluation. Key electrical and mechanical properties, including resistivity and conductivity, were assessed. The main objective was to successfully join two pieces of Cu–Nb 18% microcomposite conductor without inducing melting.

3. RESULTS AND DISCUSION

Optimal welding parameters were established by refining initial calculations through experimental testing, adjusting key variables like current density, welding time, pressure, and conductor alignment. The optimal parameters were determined to be a current density of approximately 267 A/mm^2 and a welding time of 0.4 seconds, which resulted in a weld zone temperature of 868 °C. Current densities below this threshold failed to produce seamless welds, while higher densities led to partial or complete melting of the conductor material or its matrix, compromising joint integrity. To determine the most suitable working length, two experimental series were conducted. The optimal working length was found to be between 6 and 7 mm. Wire lengths shorter than this caused rapid heat dissipation into the copper holders, preventing sufficient thermal softening of the Cu-Nb microcomposite. As a result, the yield strength of the material remained too high, leading to absent or weak joints due to insufficient plastic deformation and poor metallurgical bonding. Conversely, longer wire lengths introduced issues such as excessive bending, misalignment, or slippage of the welded ends, all of which reduce the repeatability and structural stability of the process. In a separate series of experiments, the optimal upsetting displacement was identified to be in the range of 0.9 to 1.0 mm. Displacements below this range did not produce a weld, while higher values resulted in shearing or excessive extrusion of the metal, negatively affecting joint strength and appearance. When the applied force exceeded 4300 N (corresponding to pressures above 430 MPa), severe bending, excessive material flow, and shear-type joint failures occurred. The optimal upsetting force was determined to be 4160 N, which enabled reliable joint formation without surpassing the yield strength of the conductor material (416 MPa) at the welding temperature, ensuring good mechanical integrity and consistent performance across multiple samples.

The joints produced using the optimized parameters were subjected to a series of tests to evaluate their electrical and mechanical properties. Electrical resistance was measured using the four-wire method with a precision multimeter, as shown in **Figure 3**. Based on the resistance measurements, electrical resistivity and conductivity were calculated using empirical formulas. The results of these evaluations are summarized in **Table 2**.

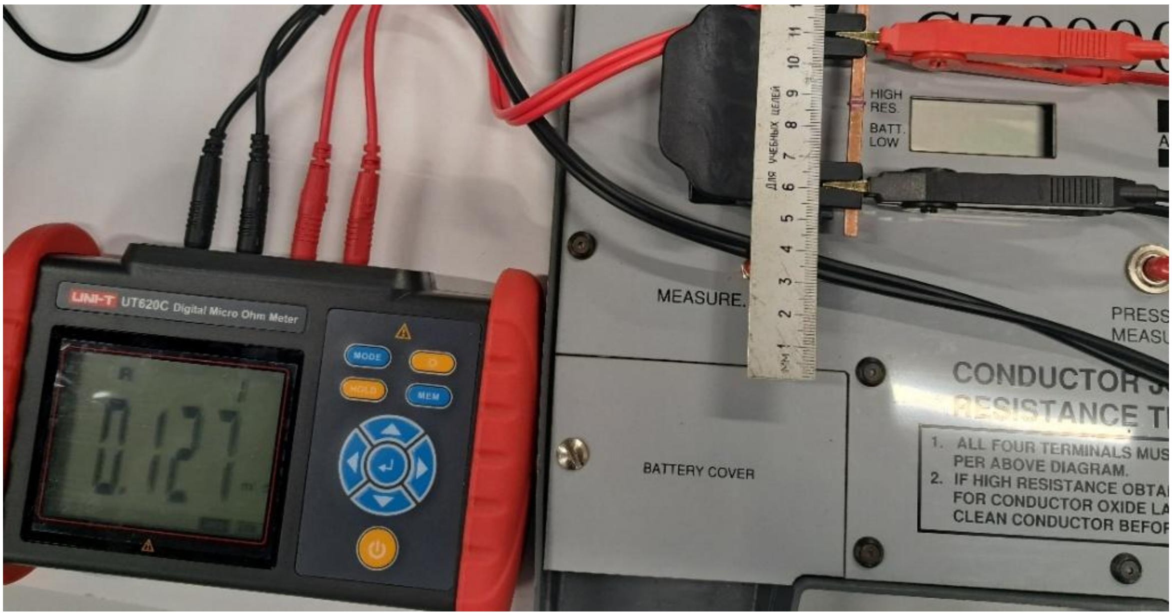

Figure 3 Four-wire electrical resistance measurement setup using UNI-T UT620C multimeter

Table 2 Measured electrical properties of resistance-welded Cu-Nb 18% microcomposite

Distance between measuring wires (mm)	Electrical resistance (μΩ)	Electrical resistivity at room temperature (μΩ cm)	Electrical conductivity (MS/m)	Electrical conductivity IACS (%)
45	127	2.67	37.49	64.65

The thermal behavior of the welded joint under electrical load was evaluated using a FLIR infrared thermal imaging camera. The temperature distribution across the joint and the surrounding base material was observed while a current of 200 A was applied for 2 minutes. **Figure 4** shows thermal images taken at the beginning of the test (a) and after 2 minutes of current flow (b). The maximum temperature observed in the weld zone reached 125 °C, while the base conductor remained significantly cooler. The temperature differences between the resistivity welding joints and the conductor during electrical current flow did not exceed the recommended value of 95 °C. This indicates good thermal stability of the joint under load. The results confirm that the resistance-welded joint can sustain high current levels without overheating or thermal degradation of joint, demonstrating its suitability for pulsed power and other high-current applications.

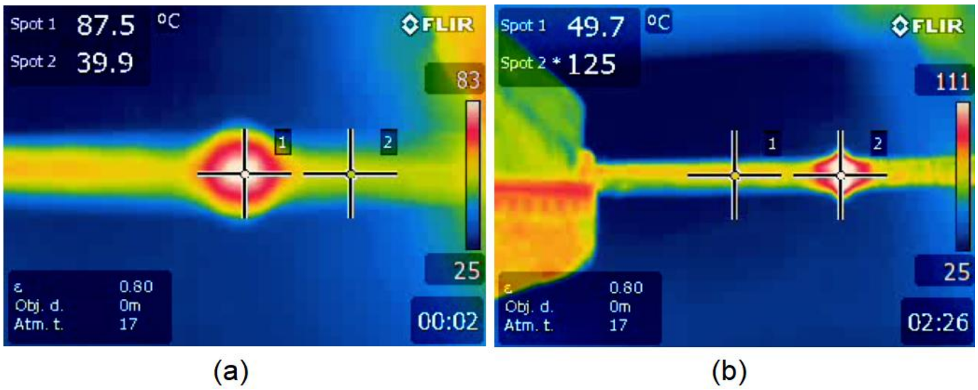

Figure 4 Distribution of the temperature in the specimen after 2 min of 200 A current flow: (a) main view; (b) enlarged view; 1, 2—measurement points in the observed area

The microstructure and geometry of the butt weld can be observed in the cross-section of the joint. As shown in **Figure 5**, the weld produced by upset resistance welding exhibits a defect-free structure, with no visible cracks, solid inclusions, voids, or shape irregularities. The bonding line of the Cu–Nb wire is clearly distinguishable in the cross-sectional view. Within the bonding region, the Nb fibers appear noticeably deformed when compared to those in the surrounding conductor material, where the fibers remain uniformly aligned along the longitudinal axis of the composite conductor. The width of the deformation zone, where the Nb fibers exhibit plastic flow and distortion, measures approximately 1 mm, which correlates with the mechanical upset displacement applied during welding. Importantly, no dendritic structures were observed in the bonded region, indicating that the process occurred entirely in the solid state without localized melting. This confirms that the upset resistance welding parameters were appropriately selected to avoid thermal heat that would exceed the melting point of either Cu or Nb, thereby preserving the microstructural integrity of the composite.

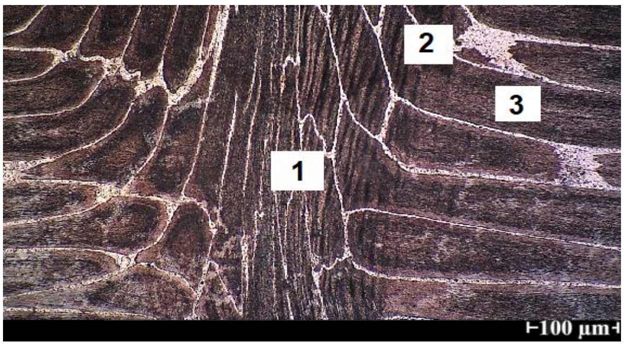

Figure 5 Longitudinal cross-section of the welded joint: 1 – joint area exhibiting plastic deformation; 2 – Cu matrix; 3 – longitudinally oriented Cu–Nb ribbons

Tensile testing of samples with welded joints showed that all specimens fractured through the weld area, as expected **Figure 6**. The welded joints withstood tensile loads of approximately 6200 N **Table 3**. Consequently, the fracture tensile stress in the joint area reached 0.62 GPa, which corresponds to 55.3% of the tensile strength of the original microcomposite wire. The elongation at fracture for the welded joint was 4.5%, which is approximately 7% higher than that of the unwelded Cu–Nb microcomposite wire. This indicates that the upset-welded joint is less brittle compared to similar joints produced by flash welding. However, mechanical strength and relative elongation of the specimens deteriorate significantly in the presence of excessive upset metal, deformation in the joint zone, misalignment of the parts to be joined, or insufficient bonding of the contact surfaces.

Table 3 Results of tensile testing of Cu-Nb 18% conductor and its welded joint

Test subject	Measured yield strength (GPa)	Measured tensile strength (GPa)	Measured maximum elongation (%)	Testing temperature (°C)
Cu-Nb wire	0.83	1.12	4.2	20
Cu-Nb welded joint	0.33	0.62	4.5	20

Figure 6 Fracture surface of the joint after tensile testing

4. CONCLUSION

This study confirmed the feasibility of joining Cu–Nb 18% microcomposite conductors using upset resistance welding without melting the base material. The resulting butt joints were clean and defect-free, showing no oxidation or porosity, which reflects effective inert gas shielding. The Nb fibers in the weld zone underwent plastic deformation and became embedded in the copper matrix, unlike the uniformly aligned fibers in the original conductor. Tensile testing showed that the welded joints retained approximately 55% of the original wire's tensile strength, which is a significant result for solid-state welding, though insufficient for highly stressed internal regions in pulsed magnets. The process produced a narrow heat-affected zone and operated below melting temperatures, preserving the composite's microstructural integrity. Despite lower strength, the joints showed improved ductility, suggesting suitability for terminal connections where mechanical loads are lower. Overall, upset resistance welding offers a promising joining method for selected Cu–Nb conductor applications.

REFERENCES

[1] ZHANG, Y., ZHANG, S., LI, S., ZHANG, X., LIU, Y., LI, J., WANG, C., ZHANG, Y., LI, J. Review of progress and challenges of key mechanical issues in high-field superconducting magnets. *National Science Review*. 2023, vol. 10, no. 3, nwad001. https://doi.org/10.1093/nsr/nwad001.

[2] BEINORAS, P., MIKALAUSKAS, G., VISHNIAKOV, N., KAPUSTYNSKYI, O. Comparative analysis of Cu–Nb microcomposite conductor welding techniques. In: *33rd International Conference on Metallurgy and Materials*, Brno: METAL 2024, 2024, pp. 269–274. https://doi.org/10.37904/metal.2024.4888.

[3] SYAHID, M. I. M., RIDHA, M. M., FARAZILA, Y., et al. Improved mechanical and electrical properties of copper-aluminum joints with highly aligned graphene reinforcement via friction stir spot welding. *Journal of Materials Research and Technology*. 2023, vol. 27, pp. 4038–4050. https://doi.org/10.1016/j.jmrt.2023.11.196.

[4] KANNE, W. R. Jr. Solid-state resistance upset welding: A process with unique advantages for advanced materials. In: *Proceedings of the Advanced Joining Technologies for New Materials II Conference*. 1994, pp. 1–18. Available from: https://digital.library.unt.edu/ark:/67531/metadc1280335/.

[5] KHEDR, M., HAMADA, A., JÄRVENPÄÄ, A., ELKATATNY, S., ABD-ELAZIEM, W. Review on the solid-state welding of steels: diffusion bonding and friction stir welding processes. *Metals*. 2023, vol. 13, no. 1, 54. https://doi.org/10.3390/met13010054.