Author(s): Yin, Shi & Hakonen, Pertti J.

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Electron-beam welded Cu-to-Ag joints for thermal contact at low temperatures

Shi Yin and Pertti Hakonen
Low Temperature Laboratory, Helsinki University of Technology, 02150 Espoo, Finland

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Electrical resistance measurements at 4.2 K on an electron-beam welded Cu-Ag joint and a simple screw-fastened Cu-Ag joint are reported. It was found that the welded joint, when annealed, gives a contact resistance that is about three times smaller than the resistances for the best screw-fastened joints.

In nuclear demagnetization cryostats working below 1 mK substantial care has to be exercised to guarantee proper thermal contact between the various constructional parts. A straightforward way to join identical metals is tungsten tip inert gas (TIG) welding that produces negligible contact resistances after annealing.[1] A more difficult problem arises when different metals, like Cu and Ag, have to be joined;[2] TIG welding cannot be used because an alloy with poor thermal conductivity is formed by the process. Typically, screw-fastened joints have been used, yielding contact resistances larger than 6 nΩ for a 1 cm^2 area in the optimal cases.[2–4] Diffusion welding has recently been applied equally successfully.[5]

The electron-beam welding technique,[6] developed in the late 1950s, has been widely used in building cryogenic apparatus. However, there are no reports so far on the thermal contact between two dissimilar metals to our knowledge[7]; between two similar metals a contact resistance of 18 nΩ has been reported for a 16-mm^2 Ag-Ag joint.[2] In this note we report electrical resistance measurements of electron-beam welded joints between copper and silver bars and compare the results with data on screw-fastened contacts. The thermal resistances can be obtained through the Wiedemann–Franz law. Electron-beam welded joints are not necessarily superior to pressed contacts because of possible alloy formation. The minimum *e*-beam spot size is on the order of 0.5 mm, so we might approximate the resulting joint by a 0.5-mm-wide alloy interface, with residual resistance ratio RRR = 5. This would give for such a joint triple the resistance value of the best screw-fastened contacts. However, the results reported in this note show that the estimated value is too large by a factor of 10.

The copper pieces were made of high quality commercial material of 99.99% purity. After vacuum (base pressure 1×10^{-5} Torr) annealing at 800 °C for 20 h the RRR was about 170. The silver pieces were of 99.9% purity and, after a similar annealing, the RRR was about 70. We use the quantity $R'=RA$ to indicate the contact resistance; R is the contact resistance, after the bulk resistances in silver and copper have been subtracted, and A is the area of the contact surface. The silver and copper bars were of 6 mm diameter. The joints were carefully machined flat, either on an end milling machine or on a lathe, without any further surface treatment.

In the screw-fastened joint [see Fig. 1(a)] the silver bar was tapped to a 3.5 mm fine thread screw hole and the copper piece was made into a matching screw. This choice was dictated by the differential thermal contraction between Ag and Cu. After annealing, the pieces were assembled together with a torque of 3 Nm. For the contact resistance we measured $R'=3.2\pm0.3$ μΩ mm^2 at 4.2 K. By heat treating this joint in vacuum at 780 °C for 20 h, we obtained a slight improvement, to $R'=2.6\pm0.3$ μΩ mm^2. In the evaluation of these values we regarded the resistance through the screw threads as much larger than through the flat contact surface, which served as a lower limit for the real case.

For a directly *e*-beam welded flat joint[8] [see Fig. 1(b)] we obtained $R'=0.55\pm0.16$ μΩ mm^2, which is close to the value $R'=0.29$ μΩ mm^2 reported for an *e*-beam welded As-As joint. To relax stresses due to rapid cooling after the *e*-beam pass, we annealed the joint in vacuum for 3 h at 750 °C which further improved the contact resistance to $R'=0.19\pm0.08$ μΩ mm^2. This small value means that the Ag-Cu alloy layer at the interface must be very thin (~ 50 μm for RRR = 5). To check this we inspected a cut joint under an electron microscope using backscattering. We found that at the outer edge there was an alloy layer about 30 μm thick, which decreased down to about 1 μm at the center of the joint. A microscope picture of the Ag-Cu interface is displayed in Fig. 2. The difference between the estimated and the observed amounts of alloy is presumably due to the small effective contact area of the joint when the alloy layer is thin. The actual small alloy formation is probably due to the swiftness of the welding, the good thermal conductivity of Cu and Ag, and the surface tension of the

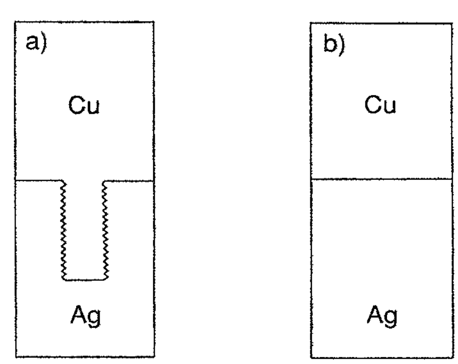

FIG. 1. Cross section of (a) the screw-fastened contact and (b) the electron-beam welded joint.

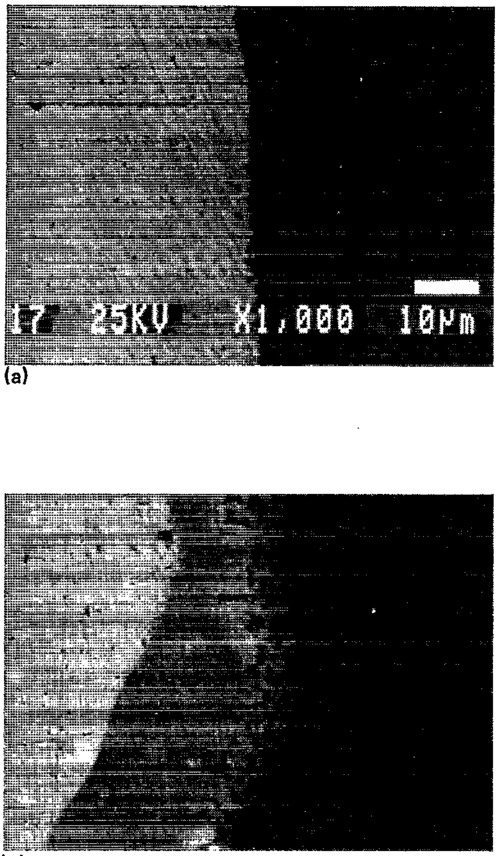

FIG. 2. Two backscattering pictures (the magnification and scale is shown in the upper one) of the Ag-Cu interface after the *e*-beam welding. The cut was made at an angle 45° off the axial direction and polished down finally with a 1 μm polishing powder. Since backscattering is stronger for heavier elements, the bright area is Ag, the dark area is Cu, and the gray area is the Cu-Ag alloy; a separate x-ray emission scan also confirmed this. (a) is close to the center and (b) is close to the edge of the joint.

melted liquids which prevents the mixing. The joint is mechanically strong.

The smallest resistances obtained so far for pressed contacts are by Mamiya *et al.* who report a value $R' = 0.63$ $\mu\Omega$ mm^2 for a Ag-Pt joint. We observe that our Ag-Cu screw-fastened joints are worse by a factor of 4 but, in fact, slightly better than the freshly sanded Cu-Cu joints reported by Lau and Zimmerman.[3] Our electron-beam welded joints clearly have the smallest contact resistance; the values are smaller than any of the screw-fastened contacts by a factor of 3 at least. Our values are also better than the diffusion welding result of 1.2 $\mu\Omega$ mm^2 for a Cu-Al joint,[5] and much better than those for typical hard-soldered joints.[1,9]

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[7] A. S. Oja, A. J. Annila, and Y. Takano also used EB welding techniques previously in our laboratory to join Ag to Cu pieces, but they did not characterize the joint.

[8] The *e*-beam weld was performed on a Leybold-Heraeus EBW 1001/15-150-CNC welding machine with the smallest beam size and a current of 6 mA at 150 kV acceleration voltage. The beam passed the rotated joint in 4 s.

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