Microstructural and Superconducting Properties of Persistent Mode Joints Between NbTi Conductors

Greg Brittles[1,2], C. Aksoy[1,3], C.R.M. Grovenor[1*], T. Bradshaw[4], C. Locket[4], S. Milward[4], S.C. Speller[1]

[1]Department of Materials, Centre for Applied Superconductivity, Univeristy of Oxford, Parks Road OX1 3PH, UK; [2] Tomamak Energy, 120A Olympic Avenue, Milton Park, Abingdon, OX14 4SA

[3]Electric and Communication Department, Faculty of Technology, Karadeniz Technical University, 61830, Trabzon, Turkey, [4]STFC, Rutherford Appleton Laboratory, Harwell Oxford, OX11 0QX, UK

Introduction

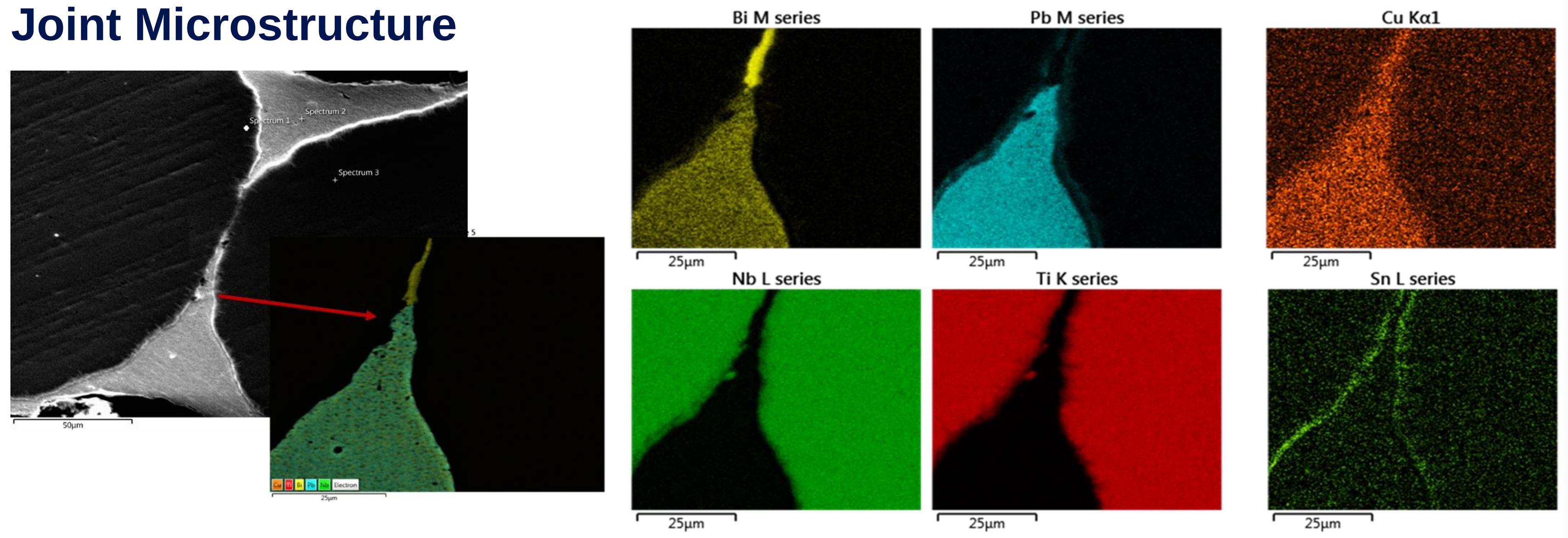
- Joints with resistance $R<10^{-12}\ \Omega$ are a requirement for persistent mode magnet manufacture.
- Although mature, practical jointing techniques exist, fundamental understanding of what controls NbTi joints remains limited [1].
- In this study, the microstructural and superconducting properties of soldered, spot welded, and cold pressed joints between monocore NbTi wires have been investigated, highlighting key metallurgical factors that control performance
- A possible solution for Pb-free, high field NbTi joints is described.

Soldered Joints

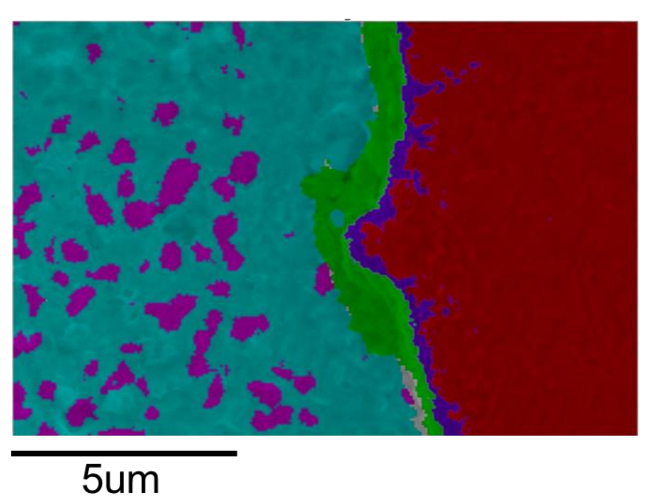
Soldering with superconducting PbBi is the industry standard jointing technique for NbTi. In this study, soldered joints were made by the standard "matrix replacement" technique, which minimises the formation of oxide on exposed filaments:

1. Dissolve Cu matrix from wires in molten Sn @ 350ºC. Filaments coated with protective Sn.
2. Dissolve Sn layer in PbBi (60:40 wt.%) @ 350ºC. Filaments coated with PbBi.
3. Twist filaments together and re-dip in PbBi over a length of ~5 mm.

Joint Microstructure



NbTi/PbBi interface (30 mins in Sn, 30 mins in PbBi)



- Nb-Ti
- Pb-Bi (ε phase)
- Bi
- Sn-Nb-Pb phase
- Bi-Nb-Ti phase

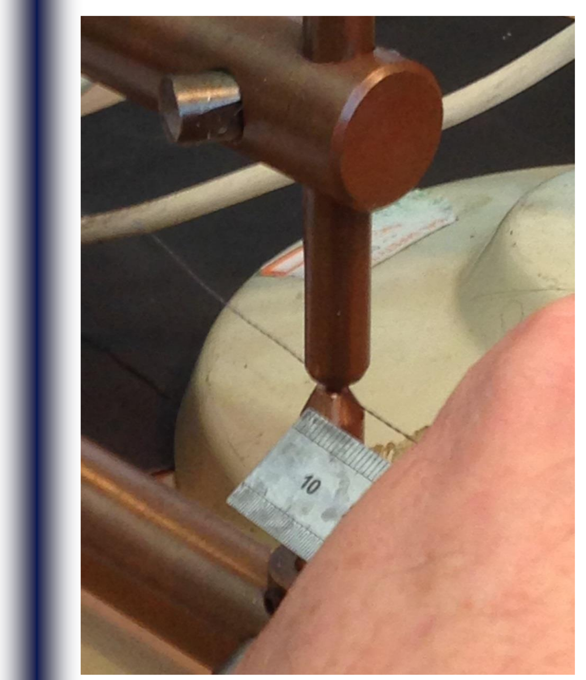
EDX phase map shows:

(1) There is some residual Sn forming a phase at the interface that is rich in Nb, Pb and Sn.

(2) There is a reaction layer containing Bi penetrating in finger-like structures into the NbTi surface.

- Reaction layers can be reduced in thickness by reducing etching times to 10 mins.
- Superconducting performance is limited by PbBi $B_{c2}(T)$, so reaction layers do not seem to be a serious problem.

Spot Welded Joints



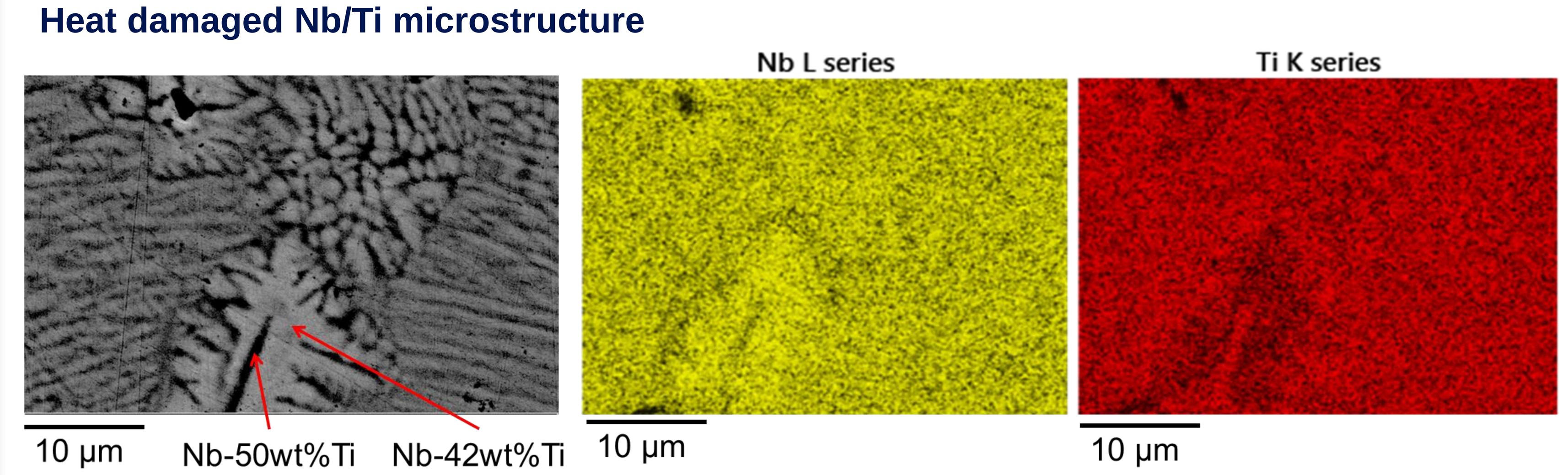
Spot welding is a process commonly used to join sheet metal, and involves passing a high current pulse through the workpieces, generating sufficient resistive heat to fuse them. NbTi filaments were joined here by:

1) Etching off the Cu matrix in nitric acid - H_2O:HNO_3 (50% vol.).
2) Twisting together the oxidised filaments
3) Spot welding between Cu electrodes over a joint length of ~ 5 mm.

Joint Microstructure

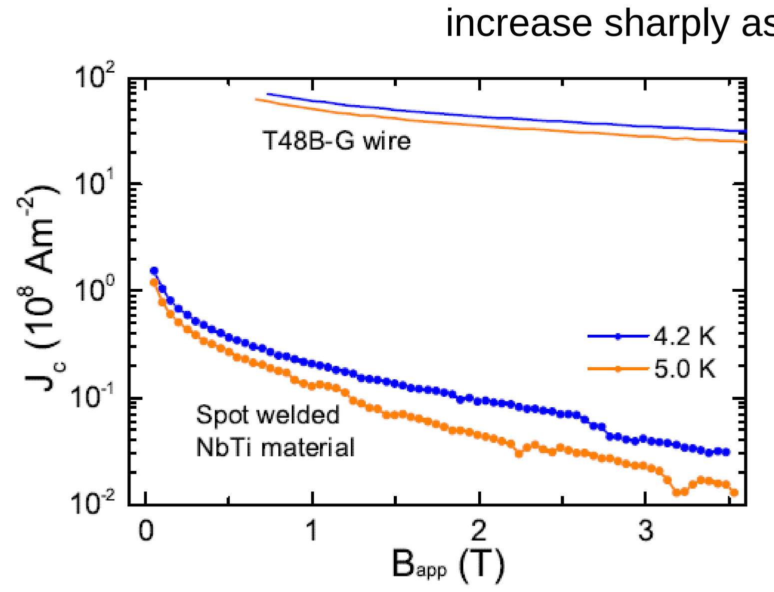
Spot-welding is very effective at fusing the filaments, completely eliminating oxides and forming a consolidated bulk. However, the temperature is raised to >2000ºC in the centre (melting the NbTi) and Cu infiltrates from the electrodes to form Cu-Nb-Ti phases.

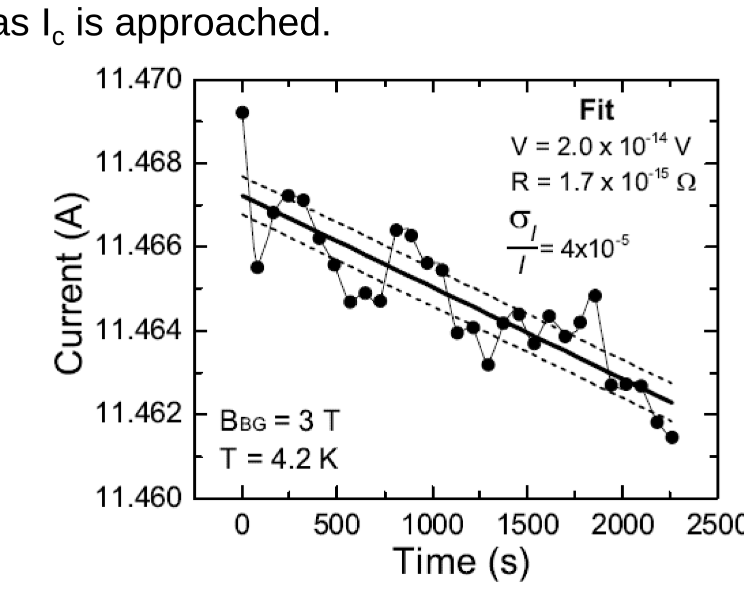
Heat damaged Nb/Ti microstructure



Joint properties

- J_c values in joint are well below those of the wire
- Even so, joint resistances are within the persistent mode regime but increase sharply as I_c is approached.





Measurement of persistent performance in spot welded joint with fitted resistance of $1.7 \times 10^{-15}\ \Omega$

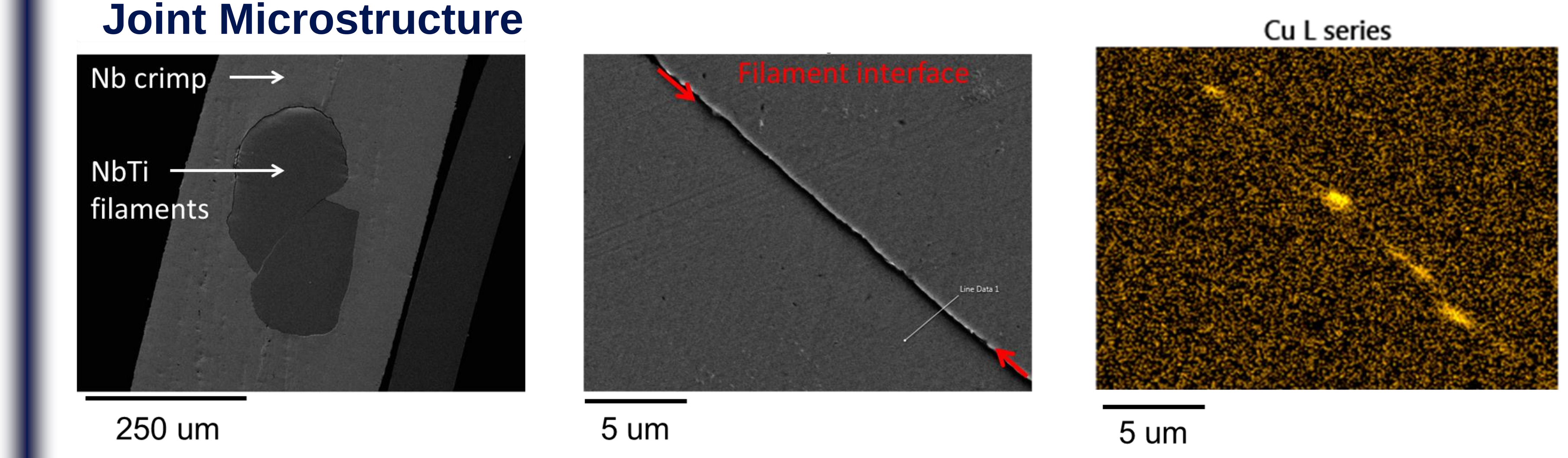
- Persistent mode joint properties can be achieved with spot welding
- However, the dendritic microstructures are typical of an as-cast microstructure in Nb-Ti, which has a wide composition range between the liquidus and solidus lines.
- The heat damaged microstructure is likely responsible for the reduced joint I_c compared to the wires. This makes spot welding hard to make reliable as a jointing technique

Cold pressed Joints

NbTi can also be joined by cold pressing bare filaments. Hydrofluoric acid (HF) is often used to remove oxides however, which is undesirable in a manufacturing environment. Here HF etching was omitted and joints were made by:

1) Etching off the Cu matrix in nitric acid - H_2O:HNO_3 (50% vol.).
2) Twisting together the oxidised filaments and slipping inside an annealed Nb crimp.
3) Pressing in a die at various pressures up to ~600 MPa.

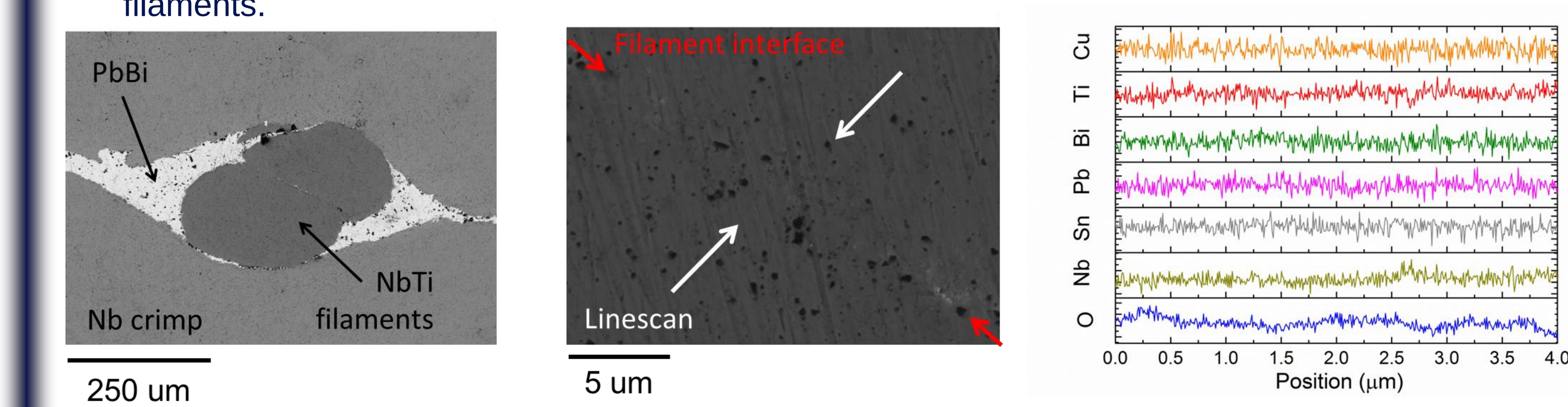
Joint Microstructure



- Inter-filament interface is poor, with residual Cu and oxides from nitric etching. HF may indeed be required.
- Appreciable currents can pass to the Nb crimp, however are limited by its inferior $B_{c2}(T)$.

Matrix replacement cold pressing

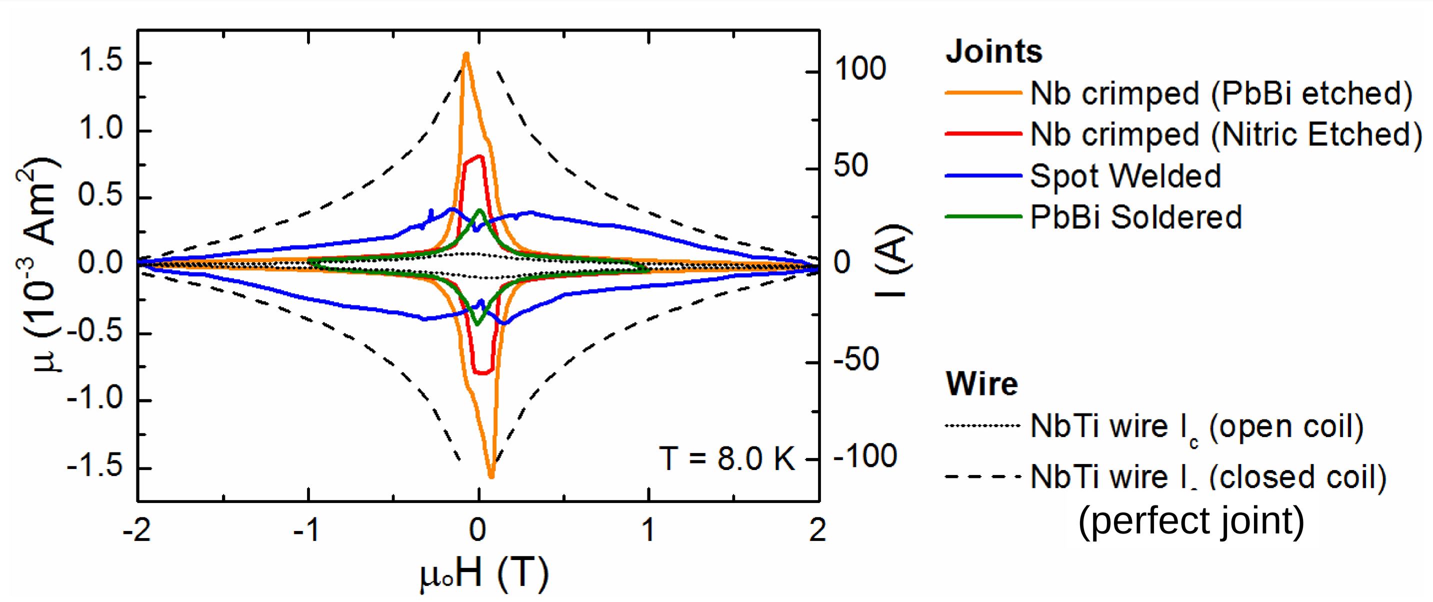
- To enhance filament bonding, nitric etching was exchanged for Sn/PbBi matrix replacement.
- Under cold pressing, the PbBi is pushed away from the interfaces, resulting in excellent bonds in some areas.
- Joint performance remains Nb-limited however due to incomplete PbBi removal between filaments.



Our proposal is to replace PbBi with Pb-free indium based solder and press above its melting temperature to enhance solder outflow and increase interfilament contact area.

Superconducting performance

- A novel SQUID magnetometry technique was developed to measure joint superconducting properties [2].
- Miniature NbTi coils are wound, jointed, and loaded into a Quantum Design MPMS XL-7.
- Currents (I) are induced and measured from coil moment ($\mu = I\pi(d/2)^2$) as a function of both field (H) and temperature (T)



- The spot welded joint has I_c reduced by heat damage.
- The soldered joint has B_{c2} limited by properties of PbBi – the Sn/Bi reaction layers are seemingly not harmful.
- The nitric etched/Nb crimped joint is limited by the B_{c2} of Nb, showing poor inter-filament bonding.
- The PbBi coated/Nb pressed joint is limited by the B_{c2} of PbBi.

Conclusions

- The microstructural and superconducting properties of a range of NbTi joints have been measured.
- Spot welding forms joints with high B_{c2}, however the process is difficult to control.
- Soldering yields a clean superconducting interface, but joints are limited by low solder B_{c2}.
- Inter-filament bonding in nitric etched cold pressed joints is poor - joint performance is limited by the crimp.
- Use of matrix replacement vastly improves interfilament bonding, and use of In-based solders and warm pressing may produce a high performance Pb-free joint.

[1] Brittles GD et al 2015, Persistent current joints between technological superconductors, Supercond. Sci. Technol. **28** 093001
[2] Brittles GD et al 2014, Rapid characterisation of persistent current joints by SQUID magnetometry, Supercond. Sci. Technol. **27**122002

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