Pb-free superconducting Solders for persistent joint between LTS wires

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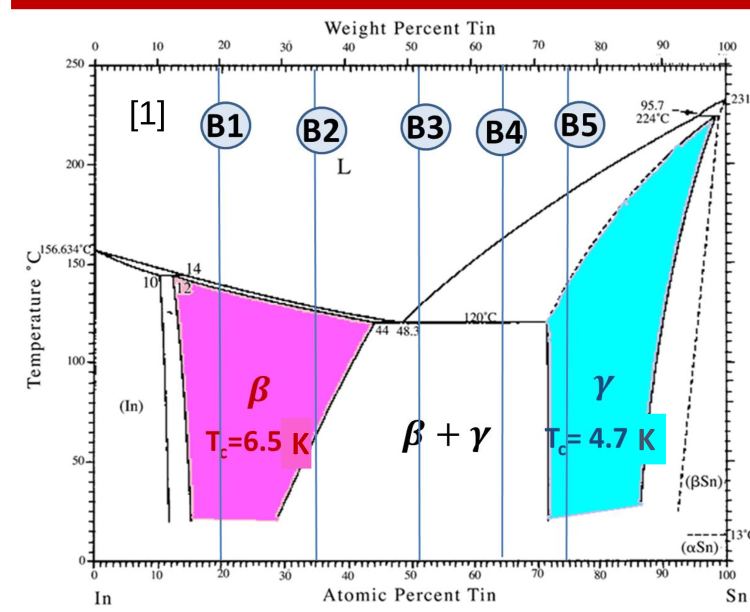
Introduction

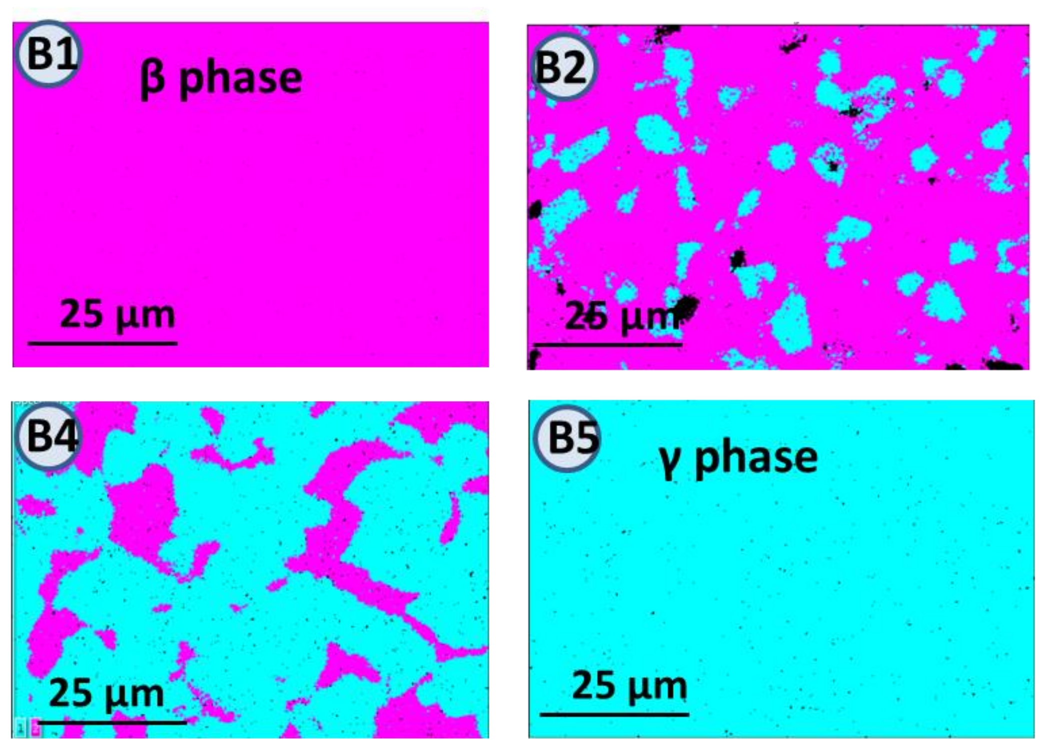
Persistent current joints are critical components of superconducting magnets. Currently soldering is the standard jointing method used in the magnet industry for technological LTS wires. The most commonly used superconducting solder materials are Pb-based alloys, however, new restrictions on the use of Pb alloys will soon become a serious concern for superconducting magnet manufacturers. Development of Pb-free solder materials is therefore a priority. We are studying the binary Sn-In and ternary Sn-In-Bi systems as potential replacements for the Pb-based alloys. In this poster we present our recent results on microstructural analysis and superconducting properties of these Pb-free solders.

Sn-In binary System



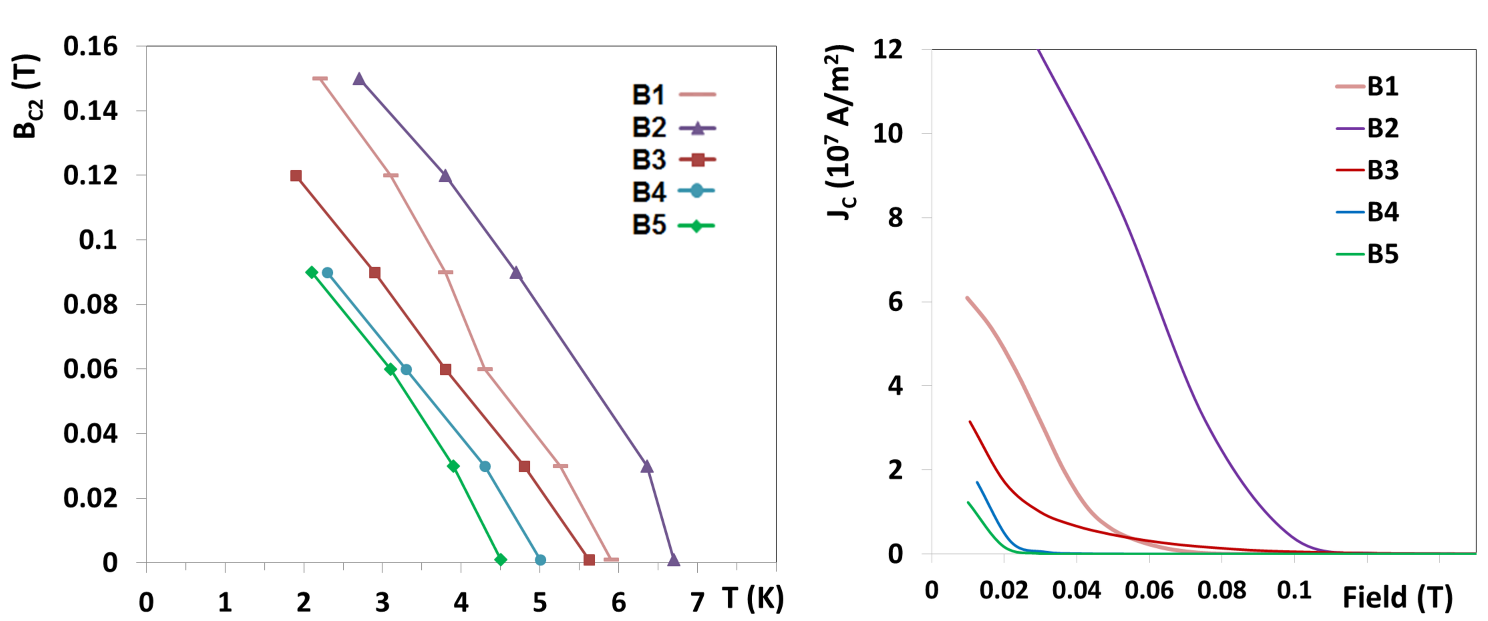
In the binary Sn-In system, five different compositions (as shown in the phase diagram) were studied. These alloys were fabricated into 2-mm cylindrical bulk samples by sucking the molten alloy into quartz tubes and cooling in air. A quench process in liquid nitrogen was also applied for the eutectic composition (B3) in order to change the microstructure and study the relation between microstructure and superconducting properties.

EDX phase maps



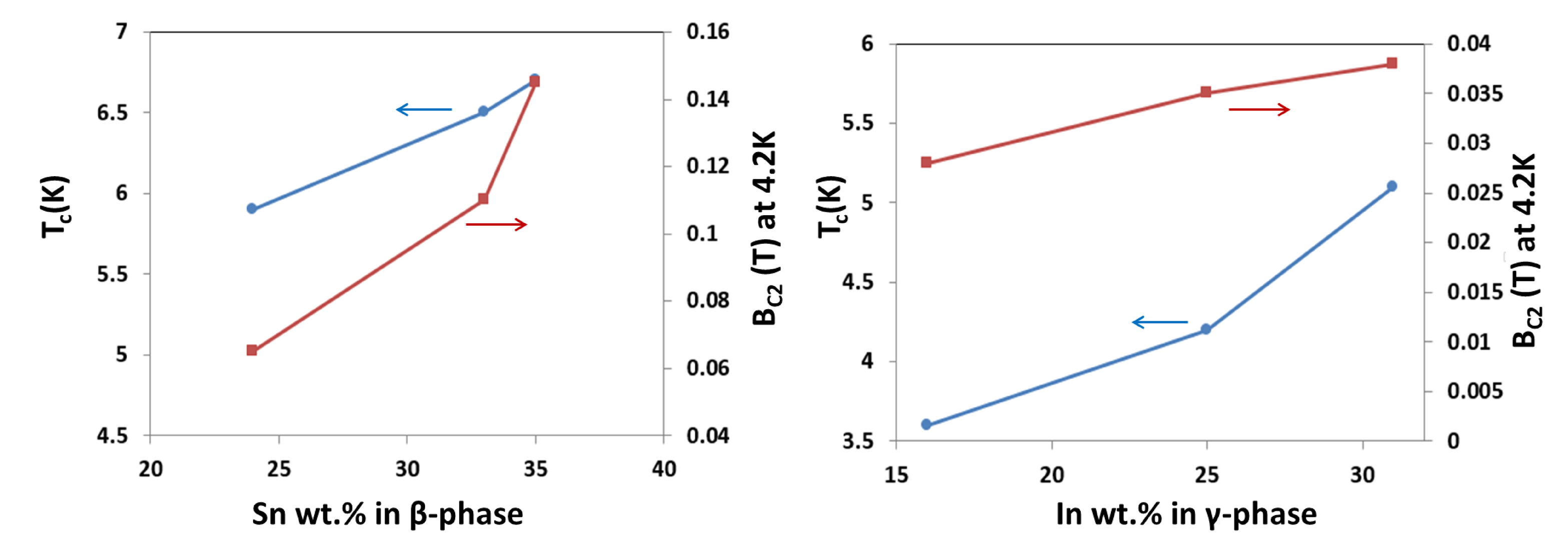
- Increasing Sn content in the composition, volume fraction of γ increases.
- As the eutectic composition, sample B3 has the finest microstructure [2].

Superconducting properties



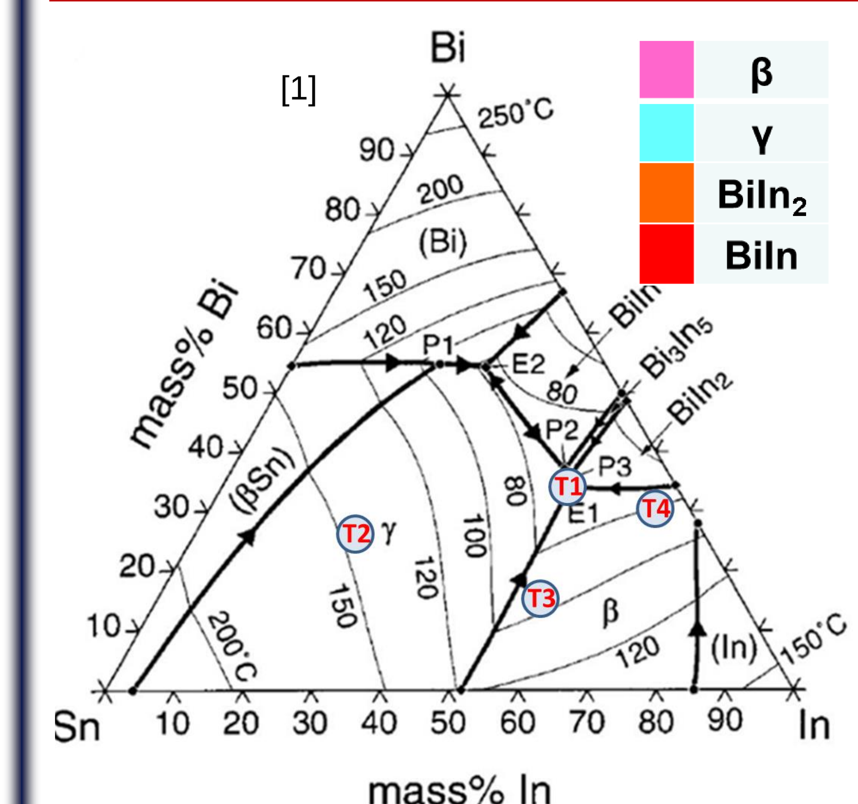
- All the Sn-In alloys show T_C above 4.2 K at low magnetic field.
- Sample B2 which contains β as the majority phase with a small volume fraction of the γ phase exhibits the highest values of T_C, B_{C2} and J_c.
- Sample B5 which is pure γ phase has the poorest superconducting properties.
- In two-phase samples, superconducting properties improve by increasing volume fraction of the β phase.

Effect of phase chemistry on superconducting properties

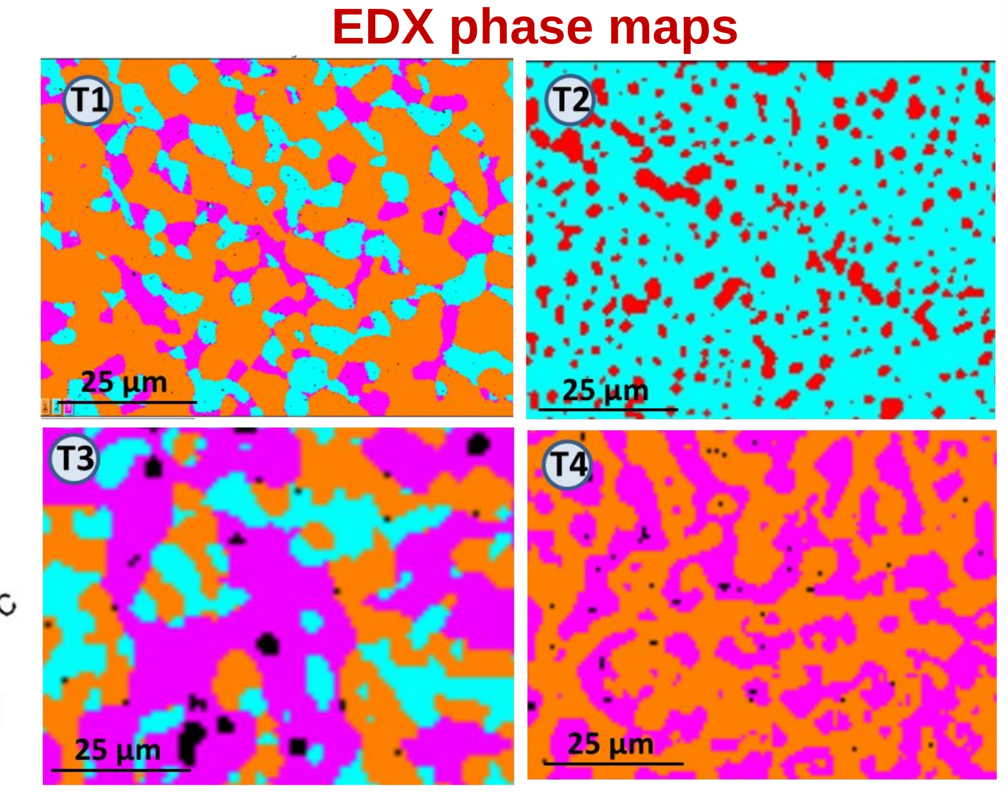


In both β and γ phases, superconducting parameters (T_c and B_{C2}) improve by increasing the solute content. As a result, in the In-rich β phase, increasing Sn content leads to higher values of T_c and B_{C2}, whereas in the Sn-rich γ phase, superconducting properties improve by increasing In content.

Sn-In-Bi Ternary System

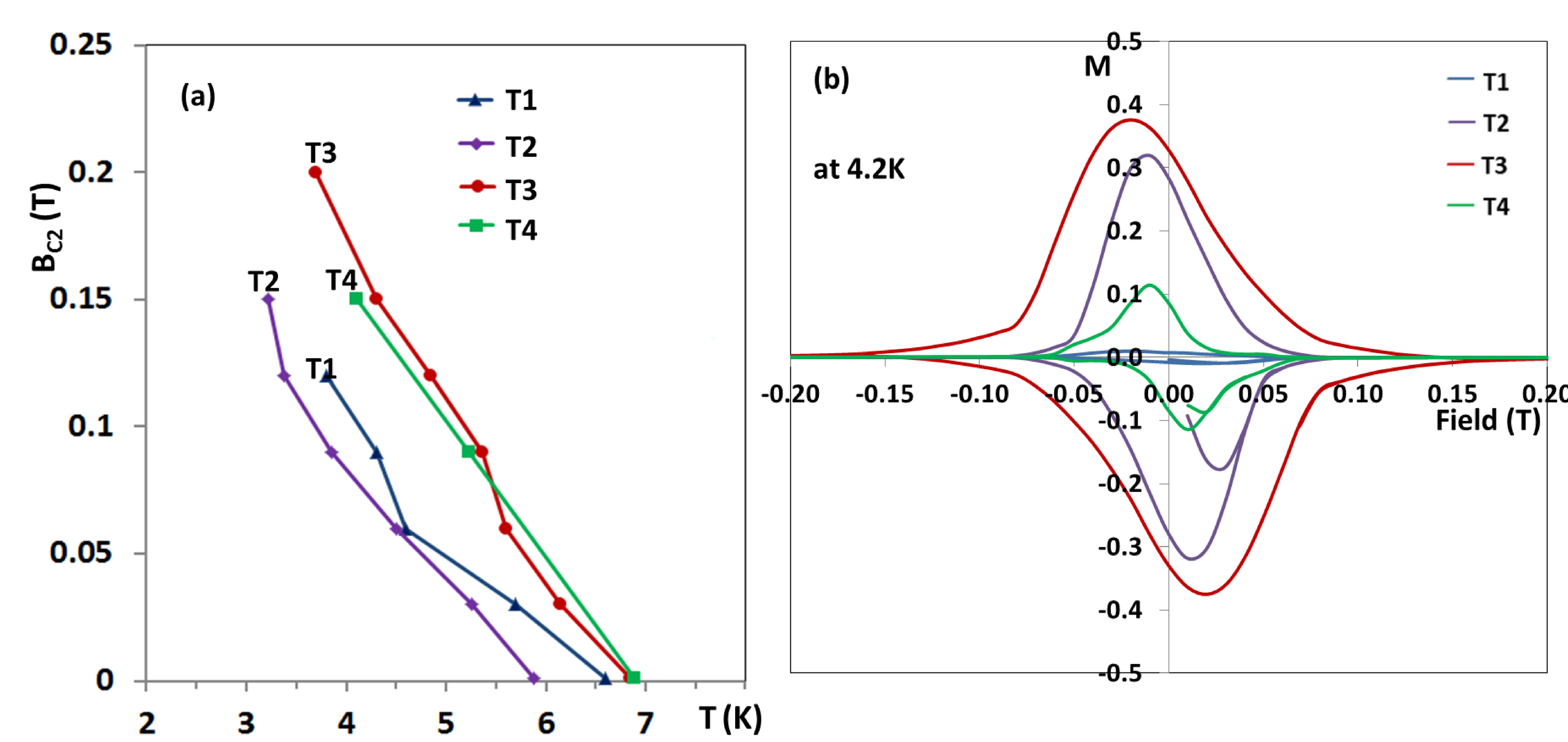


EDX phase maps



- Four different ternary alloy compositions (T1-T4) were fabricated.
- EDX phase maps indicate that a variety of microstructures with different phase fractions, chemistry and morphology can be produced.

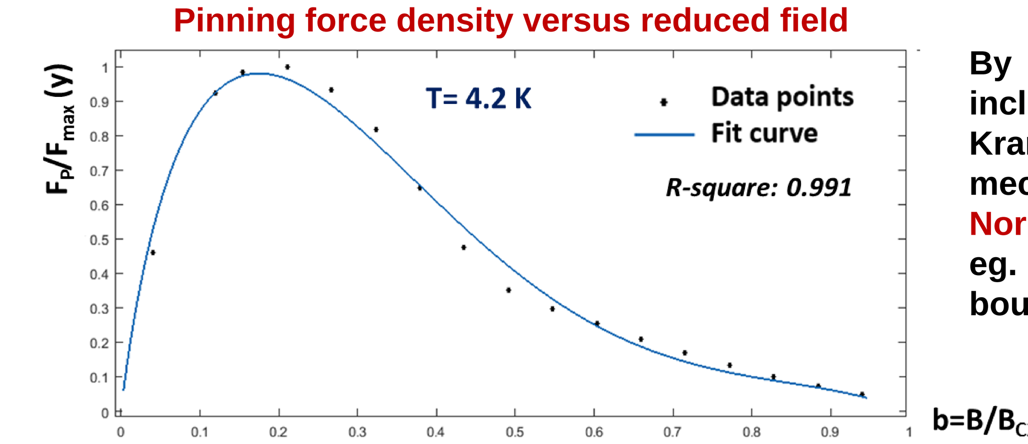
Superconducting properties



- Sample T3 exhibits the highest values of T_c (6.9K), B_{c2} (0.21T) and J_c (15×10^7A/m²) among all of the solders that we have studied in this work.

[1] Brittles et al, Supercond. Sci. Technol. 28 (2015) 093001
[2] Mousavi et al, Supercond. Sci. Technol. 29 (2015) 015012

Pinning mechanism

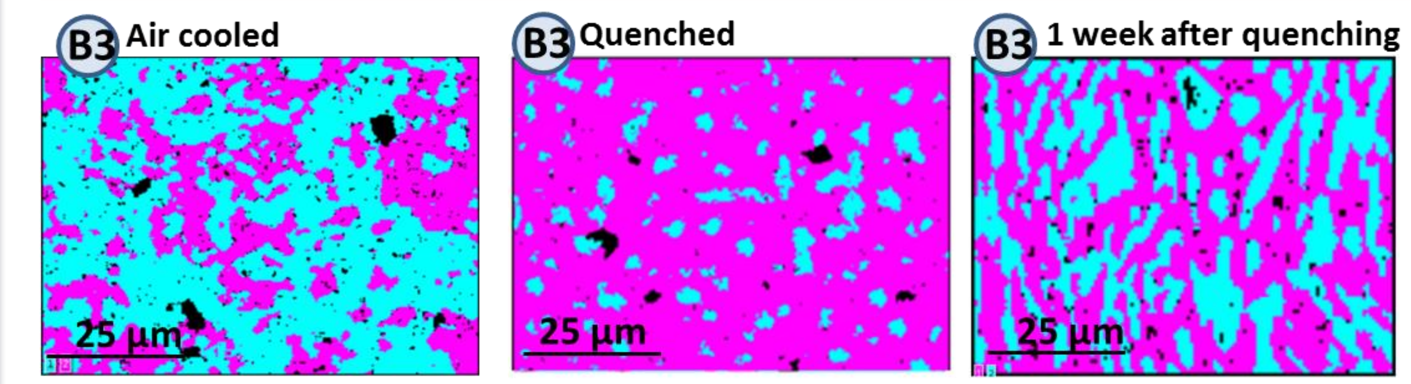


By fitting a curve with an equation including all pinning mechanisms to the Kramer plot, the active pinning mechanism was found to be Surface Normal which means all the 2D defects eg. interphase boundaries and grain boundaries are active pinning sites.

$$F_p/Fm_{ax} = \underbrace{Ab(1-b)}_{\text{Volume }\Delta\kappa} + \underbrace{Bb^{0.5}(1-b)^2}_{\text{Surface normal}} + \underbrace{Cb^{1.5}(1-b)}_{\text{Surface }\Delta\kappa} + \underbrace{Db(1-b)^2}_{\text{Point normal}} + \underbrace{Eb^2(1-b)}_{\text{Point }\Delta\kappa}$$

A	B	C	D	E
0.003	3.013	10^{-8}	10^{-4}	10^{-5}

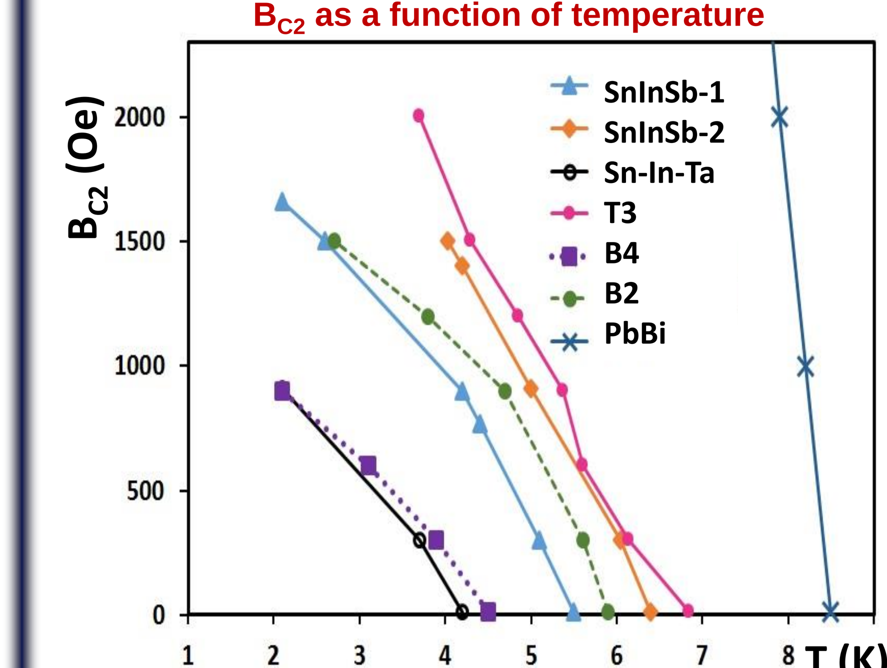
Quench effects



- The quench process results in a fine scale microstructure with the majority phase of supersaturated β phase. As a result, the superconducting properties remarkably improve by quenching.

Sample B3	Phases (phase fraction)	Chemistry of phases	Tc (K)	Bc_2 (T) at 4.2 K	J_C (10^7A/m²) at T=4.2 K, B=0.03T	Boundary length per unit area (um/µm²)
(Air-cooled)	β (48%)+γ (52%)	γ:In32Sn68 β:In78Sn22	5.6	0.04	3.1	0.35
(Quenched)	β (84%)+γ (16%)	β:In62Sn38 γ:In33Sn67	6.7	0.145	12.2	0.41
(1 week after quenching)	β (40%)+γ (60%)	β:In72Sn28 γ:In32Sn68	6.1	0.08	8.5	0.26

Sn-In-A (A:Sb,Ta)



- To investigate the superconducting properties of the other Pb-free solders, several samples were studied in Sn-In-Sb and Sn-Ta systems.

  SnInSb-1: (65Sn-35In-5Sb), SnInSb-2 (35Sn-50In-5Sb), SnTa: 30Sn-60In-10Ta (all wt%)

- In the Sn-In-Sb system, up to 2-3wt% Sb can be dissolved into the SnIn phases, and the excess Sb will form the islands of an SbIn-rich phase.
- In the Sn-In-Ta system, no solubility of Ta in the Sn-In phases was observed, and the microstructure is composed of a matrix of Sn-In phases with unreacted Ta particles, and T_c and B_{c2} values show no improvement.

Summary

- Both Sn-In and Sn-In-Bi systems offer low-melting point superconducting alloys.
- β phase has better superconducting properties than the γ phase, as a result by increasing the phase fraction of the β phase, overall superconducting properties improve.
- In both β and γ phases, superconducting properties improve by increasing the solute content.
- The active pinning mechanism is surface normal (ie 2D defects are active pinning sites). By changing the cooling rate and subsequently the scale of microstructure, superconducting properties can be manipulated. These alloys age considerably even at room temperature.
- Ternary Sn-In-Bi alloys have better superconducting properties than the binary Sn-In alloys, but still much lower than Pb-Bi.

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