The figures in this version of the paper are editable. All data are accessible

In addition, we have also produced an Excel file which has all the data in the figures available on request from Prof. Hampshire

Superconducting and Mechanical Properties of Low-Temperature Solders for Joints

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***Abstract*—All large superconducting applications require electrical connections between superconductors or between superconductors and other metallic parts of the systems. Such connections are essential components for these applications and are usually made by melting the solder (or soft soldering). In general, the melting point, electrical resistivity, mechanical and wetting properties and toxicity are all important criteria when choosing the best solder for a specific application. If the solder itself is superconducting under the operating conditions of the application then there is also the possibility of extremely low resistance joints. In this work we report on the superconducting properties of six low melting point solders: $Bi_{49}Pb_{18}In_{21}Sn_{12}$ (Cerrolow 136), $Pb_{20}Sn_{34}Bi_{46}$, $Pb_{20}Sn_{60}Bi_{20}$, $In_{52}Sn_{48}$, $Pb_{38}Sn_{62}$ and $Pb_{57}Bi_{36}Sb_7$ and the mechanical properties of three of the six solders ($Pb_{38}Sn_{62}$, Cerrolow 136 and $Pb_{20}Sn_{34}Bi_{46}$). We have found that all the solders except $Pb_{38}Sn_{62}$ and $In_{52}Sn_{48}$ have relatively high upper critical fields (higher than 2 T) at temperatures lower than 3 K. Although the good ductility and high maximum fracture elongation of $Pb_{38}Sn_{62}$ is useful when using low temperature superconductors, other solders may be preferred with high temperature superconductors because their lower melting temperatures mean they are less likely to delaminate them.**

***Index Terms*— Coated conductor, solder, soldered joint, tensile test.**

I. Introduction

SOLDERED joints are essential components of all large superconducting applications. These applications include superconducting power lines, high-field magnets for MRI machines, nuclear fusion reactors and particle accelerators. To ensure reliable operation of soldered joints, a detailed knowledge and understanding of all the relevant electrical, thermal and mechanical properties of the solder are required. As part of the first screening of solders for joints, we usually consider electrical resistivity, melting point, mechanical strength, wetting properties and toxicity. The importance of each of the solder's properties can differ from one application to another. If high-temperature superconducting coated conductors are involved then the melting point of the solders used must be low. A high soldering temperature can lead to delamination of the coated conductors and change of oxygen content in the superconducting layer. These effects will degrade the superconducting properties of the coated conductors [1]. However for joints using low temperature superconductors, the superconducting materials are much more chemically and structurally stable and melting point of the solder is not so important. The mechanical properties of commonly used solders such as $Pb_{38}Sn_{62}$ have been studied extensively [2]. However, the superconducting properties of many low melting point solders that are potential materials for joints have not yet studied in detail. In this paper we find that the cooling rate during the solidification of the solder strongly affects its mechanical properties, most probably because of the different microstructures formed [3]. Hence we present a study of both the superconducting and mechanical properties of six low melting point solders, so that with good control of sample preparation, we identify good candidate solders for superconducting applications.

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II. Experiment

A. Sample preparation

All the samples except the Cerrolow 136 were fabricated in-house at Durham. Cerrolow 136 was obtained from a commercial company. All the constituent elemental metals of each solder were placed into a crucible. The crucible was then heated to well above the melting point of the solder (cf Tables 1 and 2). Heat was removed when the molten solder was formed and the crucible was allowed to cool down to room temperature in air. The samples for mechanical tests were made by re-melting the solders at temperatures well above their melting temperatures. Each sample was then cooled down to room temperature at a constant rate in air. The cooling process was monitored by two thermocouples to ensure there was no thermal gradient across the sample. We found that controlled cooling rates were essential to ensure reproducibility of the experimental results. Table 1 gives the maximum temperature and cooling rate used during the fabrication of the sample for the mechanical tests. The samples were formed as rectangular slabs with typical dimensions of 80 × 4.4 × 2.2 mm^3. For ac magnetic moment measurements, a small piece of each solder was cut and mounted in a plastic straw.

B. Experimental procedures

All mechanical tests were carried out using a Mecmesin Multi-Test 2.5-d tensile & compression test system. A pair of

Table 1: Maximum temperature used to melt the samples and the cooling rate used to fabricate the solder samples for mechanical tests

Solder Alloy	Max. Temp. °C	Cooling Rate °C/second
$Pb_{38}Sn_{62}$	250	0.100
Cerrolow-136 ($Pb_{18}Sn_{12}Bi_{49}In_{21}$)	75	0.036
$Pb_{20}Sn_{34}Bi_{46}$	120	0.060

Table 2: Melting point, resistivity and superconducting properties of the solders studied

Solder Alloy	Melting Point °C	ρ (room temp) 10^{-7} Ω·m	ρ (77 K) 10^{-7} Ω·m	T_c K	B_{c2} (0K) T
$Bi_{49}Pb_{18}In_{21}Sn_{12}$ (Cerrolow 136)	58	9.4	8.1	6.4	3.3
$Pb_{20}Sn_{34}Bi_{46}$	~ 96	5.5	2.6	8.4	2.3
$Pb_{20}Sn_{60}Bi_{20}$	~ 170	2.6	1.1	8.5	2.2
$In_{52}Sn_{48}$	118	2.6	1.3	6.4	0.34
$Pb_{38}Sn_{62}$	183	1.5	0.48	7.3	0.30
$Pb_{57}Bi_{36}Sb_7$	200 – 230	6.1	3.7	8.5	2.5

Nyilas-type extensometers [4] were used to measure the elongation of each sample at different strain rates. These very sensitive extensometers consist of a copper-beryllium frame and are equipped with a Wheatstone bridge of strain gauges. The double extensometer configuration also has the advantage of mitigating against experimental errors resulting from sample distortion. Ac. magnetic moment measurements of all the solder samples were performed in a Quantum Design Physical Properties Measurement System in magnetic fields up to 2 T and at temperatures from room temperature down to 2 K. The resistivity of the solders were measured using the standard dc four-terminal method.

III. Results and Discussions

A. *Superconducting properties*

$B_{c2}(T)$ of Cerrolow 136, $Pb_{20}Sn_{34}Bi_{46}$, $Pb_{20}Sn_{60}Bi_{20}$ and $Pb_{57}Bi_{36}Sb_7$ was determined from the ac magnetic moment measurements. The values of $B_{c2}(T)$ for these solders were obtained from the onset of the superconducting transition in decreasing temperature. Figure 1 shows typical ac magnetic moment against temperature curves at different applied magnetic fields for one of the solders studied. $B_{c2}(T)$ of $Pb_{38}Sn_{62}$ or $In_{52}Sn_{48}$ was obtained from resistivity measurements. Typical resistivity data for $Pb_{38}Sn_{62}$ are shown in Figure 2 $B_{c2}(0)$ and the transition temperature (T_c) were obtained by fitting the $B_{c2}(T)$ data with the Werthamer-Helfand-Hohenberg (W-H-H) equation [5] as shown in Figure 3. Melting point, resistivity, $B_{c2}(0)$ and T_c of all solders are summarized in Table 2. $Pb_{38}Sn_{62}$ or $In_{52}Sn_{48}$ have $B_{c2}(T)$ values almost 10 times lower than the other solders and relatively low T_c values. The solders with higher $B_{c2}(0)$ values open the possibility of very low resistance joints if the joints are located in low field regions for a given application. Some also have substantially lower melting points (i.e. all except

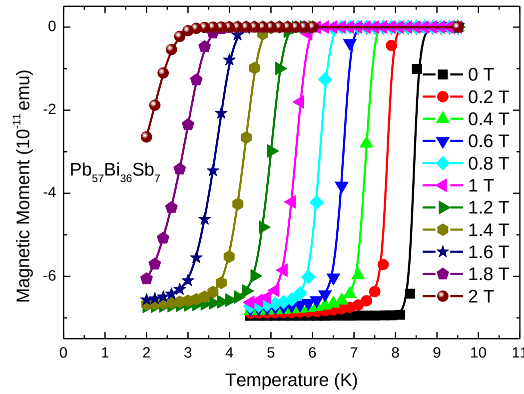

Figure 1: Ac. magnetic moment against temperature in different applied magnetic fields for $Pb_{57}Bi_{36}Sb_7$. Lines are guides to the eye.

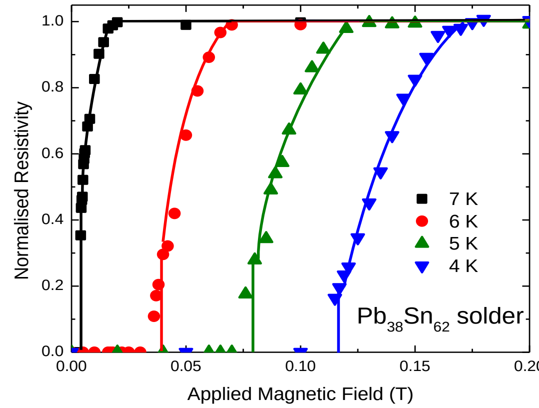

Figure 2: Normalized resistivity of $Pb_{38}Sn_{62}$ solder as a function of magnetic field at different temperatures. Lines are guides to the eye.

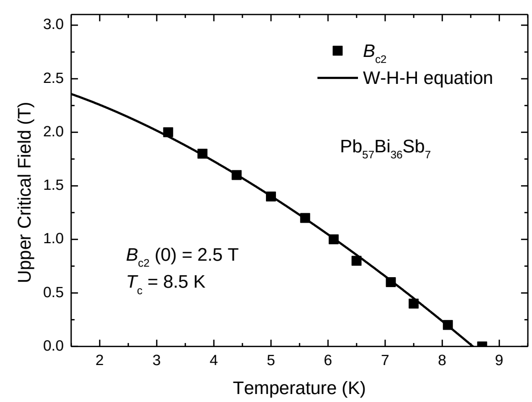

Figure 3: Upper critical field as a function of temperature for $Pb_{57}Bi_{36}Sb_7$. Curves are fitted using the W-H-H equation.

$Pb_{57}Bi_{36}Sb_7$) which can ensure there is no degradation for example to HTS coated conductors during the soldering process. Equally if low temperature superconductors are being used and the operating conditions for the joints are at high magnetic field, then the soldering temperature need not be important and $Pb_{38}Sn_{62}$ may be a better solder to use because of its much lower resistivity and better mechanical properties.

B. Mechanical tests

Figure 4 displays a typical stress-strain curve for the samples measured in this work. The elastic modulus, tensile strength and fracture elongation were extracted from these curves at different strain rates for each sample (see Figure 4). Figure 5 shows the stress/strain curves for $Pb_{20}Sn_{34}Bi_{46}$ at different strain rates which shows the strain rate has a substantial effect on the solder's mechanical properties. The figure also demonstrates the good reproducibility obtained for nominally identical samples. The high strain rate dependence of mechanical properties is well established for both Pb-Sn and Pb-free solders in the literature [6]. Figure 6 and 7 show the elastic modulus (E) and tensile strength (σ_T) against strain rate for all three solders. Among these 3 materials, $Pb_{38}Sn_{62}$ has the best mechanical properties then Cerrolow and finally $Pb_{20}Sn_{34}Bi_{46}$. The values of E and σ_T differ by ~30 % for $Pb_{38}Sn_{62}$ and Cerrolow 136. Figure 8 and Figure 9 display the fracture elongation of the samples as a function of strain rate. In Figure 8, the fracture elongation was measured using the whole length (~44 mm) of the sample between the grips of the

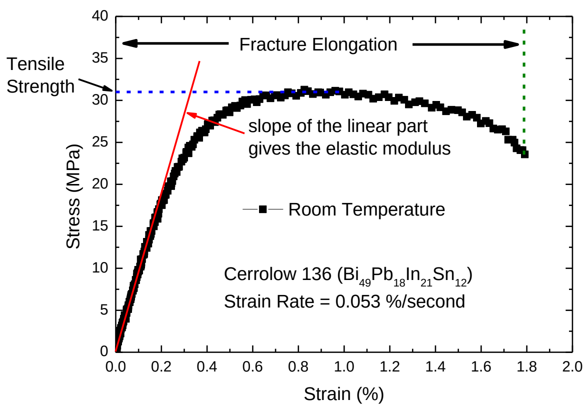

Figure 4: Stress-strain curve for $Bi_{49}Pb_{18}In_{21}Sn_{12}$ at a strain rate of 0.053 %/second.

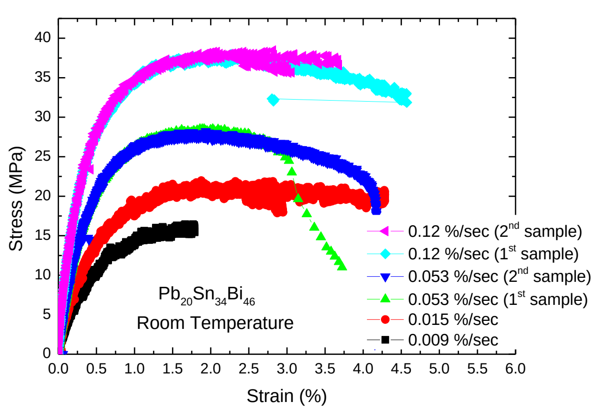

Figure 5: Stress versus strain at different strain rates for $Pb_{20}Sn_{34}Bi_{46}$.

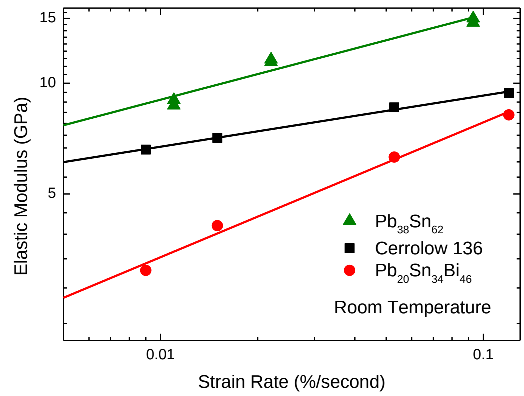

Figure 6: Elastic modulus versus strain rate for three solders on a log-log scale. Lines are guides to the eye.

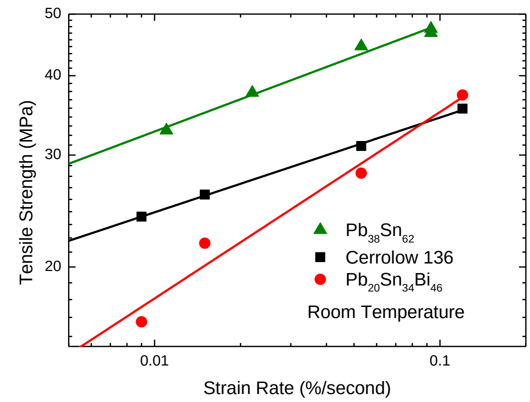

Figure 7: Tensile strength verses strain rate for three solders on a log-log scale. Lines are guides to the eye.

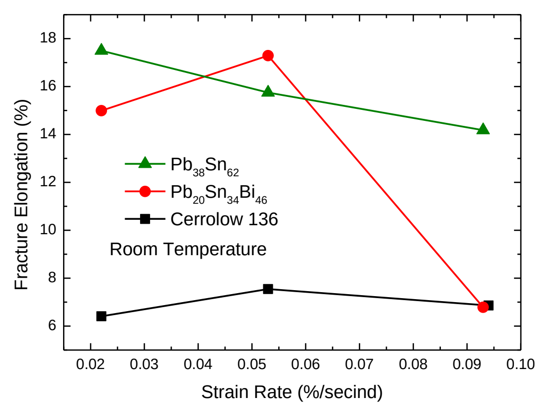

Figure 8: Fracture elongation as a function of strain rate for three solders at room temperature. Elongation was calculated from measuring the full length of the broken sample (~44 mm in length). Lines are guides to the eye.

stress/strain measuring machine after failure. Whereas in Figure 9, the maximum fracture elongation was measured in that part of the samples (25 mm in length) outside of the breaking point of the sample. Both of these figures show the

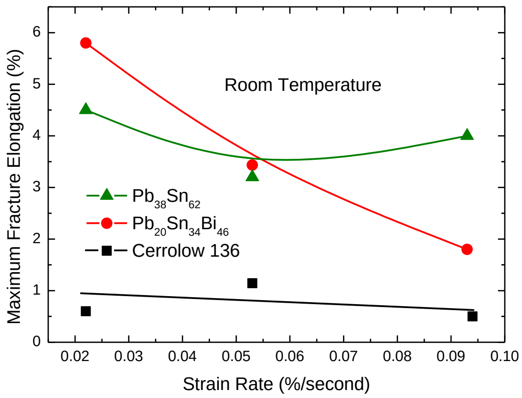

Figure 9: Maximum fracture elongation as a function of strain rate for three solders at room temperature. Elongation was measured in the middle section of the sample (25 mm in length) which was unbroken - outside the breaking point. Lines are guides to the eye.

fracture elongation of $Pb_{38}Sn_{62}$ is several times higher than that of Cerrolow 136. We conclude that the much lower values in Figure 9 compared to Figure 8 are much more relevant and useful for practical assessment of the best solder for joints. Consistent with our extensive experience making soldered joints between HTS coated conductors and copper-beryllium using both $Pb_{38}Sn_{62}$ and Cerrolow 136 and then straining the joints, we found Cerrolow 136 soldered joints sometimes came apart when they were cooled down to 4.2 K from room temperature and often failed at very low strain values at about 0.5 %. Such behaviour very seldom happened with $Pb_{38}Sn_{62}$ soldered joints.

IV. Conclusion and Future Work

We have measured some of the electrical, mechanical and superconducting properties of some relatively high B_{c2} solders. These solders can provide good properties for applications requiring joints. We have reported that at room temperature the maximum fracture elongation and ductility of $Pb_{38}Sn_{62}$ is much greater than Cerrolow 136 and that a measurement of the maximum fracture elongation provides a good measure of the solder's mechanical properties for joints. In the future, we are going to extend the measurements to low temperatures, include wettability tests and expand the solder selection to contain other increasingly used lead-free solders such as $Sn_{96.5}Ag_3Cu_{0.5}$ [7].

V. References

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