The Effect of Hot Isostatic Pressing on the Strain Tolerance of the Critical Current Density Found in Modified Jelly Roll Nb_3Sn Wires

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Abstract — **The critical current density of Hot Isostatic Pressed (HIP'ed) and unHIP'ed Nb_3Sn Modified Jelly Roll wires has been measured as a function of magnetic field and of strain at 4.2 K. The reversibility of critical current density was investigated for both wires. The critical current and upper critical field were decreased for the HIP'ed sample. The reduced upper critical field of the HIP'ed wire was found to be less sensitive to strain than the unHIP'ed wire. The index (m) of the flux pinning scaling law is found to have increased from 0.86 to 2.14 as a result of the HIP processing.**

I. Introduction

Modified Jelly Roll [1] (MJR) Nb_3Sn superconducting wires have several advantages over bronze processed multifilamentary wires. They are generally easier to fabricate, and give more flexibility for the final configuration of the wire. This flexibility in the design allows customised wires to be fabricated for different applications. For high field applications, not only the magnitude but also the strain tolerance of the critical current density (J_C) are important. Work has been reported on Hot Isostatically Pressed (HIP'ed) Nb_3Sn wires at low magnetic fields [2] between 3 T and 8 T which showed an improvement in the strain tolerance of J_C that could potentially be repeated at higher fields. It is known that Kirkendall voids are present near the grain boundaries in Nb_3Sn wires and that a high pressure reaction on reacted wires is sufficient to eliminate the voids [2], [3]. Furthermore, work on high temperature superconductors has demonstrated that J_C can be increased by improving the current transport across grain boundaries. These results have led us to consider whether HIP'ing can be used to improve the properties of MJR wires in high magnetic fields.

In this paper we investigate whether the critical current density of wires optimised at ambient pressure can be further improved by HIP'ing. We also report on the effect of HIP'ing on the strain tolerance of the upper critical field.

The paper is arranged as follows. Sections II and III describe the experimental procedure used and present the results obtained. Section IV analyses the results within the framework of a scaling law [4]. Finally the effects of HIP'ing on the critical current and scaling law parameters are discussed and the important conclusions drawn.

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II. Experimental

The wires examined in this study were 0.5 mm diameter internal-tin MJR wires with niobium diffusion barriers [5]. The wire was wound loosely on to a steel reaction mandrel with a 0.5 mm deep 60° V-groove. The mandrel had been subjected to a 3 hour pre-reaction heat treatment in oxygen in an effort to reduce diffusion bonding to it by the sample. The wires were reacted in argon at 1 atmosphere pressure using the manufacturers heat treatment procedure of 210° C for 100h followed by 340° C for 48 h and finally 650° C for 180h. The HIP'ed wire was then subjected to a further heat treatment of 750° C for 6 hours in argon at 2000 atm.

The reacted wires were then transferred on to a 2% beryllium doped copper alloy spring. The pitch on the spring was 0.635 cm so that the wire was orientated at an angle of 5.3° from perpendicular to the magnetic field. The spring and sample were partially electroplated with copper. The wire was then soldered to the spring in order to reduce Joule heating and to provide some protection for the wire against the Lorentz forces that occur during the measurement.

To check the homogeneity of the wires, HIP'ed and unHIP'ed samples were also reacted directly on the critical current sample holders. This eliminated the need to transfer the sample after reaction so values of J_C could be measured with little risk of handling damage.

Measurements were performed on the Durham University Variable Temperature Strain Probe at 4.2 K [6]. The sample was directly immersed in helium and the critical current was measured using a standard 4-terminal resistance measurement at a criterion of 1 $\mu V cm^{-1}$. Current was provided using a 500 Amp power supply built in-house. The voltage was measured using a Keithley 182 voltmeter. The critical current was measured as a function of applied magnetic field at constant strain. The magnetic field was applied using a superconducting magnet providing fields up to 15 T. Once the variation of critical current with applied magnetic field was measured at one strain, the strain was changed, and the J_C measurements repeated. The strain was initially increased from 0% to about 0.45% strain. The strain was then reduced back to 0% to investigate the reversibility of critical current under strain. The strain was then increased to 0.7% (which is the elastic limit of the spring) and reduced to 0% again. The increments of strain were 0.057%, so that a good description of the strain tolerance of the wire could be found, except in the final release of strain where measurements were performed at 0.63%, 0.23% and 0% strain.

III. RESULTS

Figs. 1 and 2 show the engineering critical current density, J_e (the critical current density for the entire wire), as a function of strain for the unHIP'ed and HIP'ed wires respectively. The data were both taken during the second increase of strain. It can be seen that the thermal precompression for the unHIP'ed wire is 0.23% and 0.27% for the HIP'ed wire. The variation in the critical current values for different sections of both the HIP'ed and unHIP'ed wires was about 10%. The critical currents measured for both types of wires on springs or reaction mandrels were in good agreement.

Fig. 3 characterises the reversibility of the critical current density at 14 T and 15 T as a function of strain. The clear symbols describe the first increase of strain, whereas the first decrease and second increase are represented by black and grey symbols respectively. It can be seen that the second increase in strain gives slightly larger critical current densities than the equivalent first cycle. However, the first cycle does appear to be almost reversible with applied strain in all cases. The reversibility is also evident in Fig. 4. This shows the electric field-current density characteristics at 10 and 12 T for the HIP'ed wire as well as 14 and 15 T for the unHIP'ed sample. The first increase and decrease of strain overlap, confirming the reversibility seen in Fig. 3. Again, the second increase in strain has higher J_e values than the first cycle, and a degradation in J_e can be seen on the final decrease of strain. It is evident that the degradation is more noticeable at lower electric fields, and is larger at higher current densities.

IV. ANALYSIS

Fig.5. shows a typical Kramer plot [7] for the unHIP'ed wire during the second increase in strain calculated from the data in Fig. 1. The data at each strain were fitted to a line of best fit so that values of upper critical field (B_{C2}*) and maximum pinning force ($F_{p\text{-}max}$) could be calculated. This fitting procedure was repeated for the HIP'ed wire.

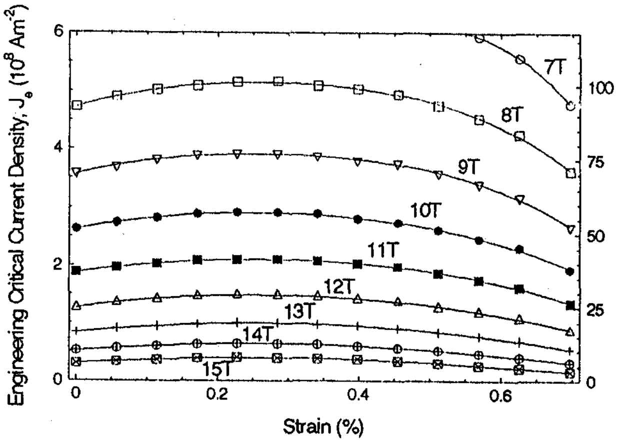

Fig. 2. Engineering critical current density as a function of strain and applied magnetic field for the HIP'ed wire. Measurements were taken during the second increase of strain.

The reduced upper critical field as a function of intrinsic strain for the first cycle and second increase of strain for both wires are shown in Fig. 6. The values of upper critical field for the unHIP'ed and HIP'ed samples at the peak were 23.83T and 18.13 T respectively. These values were measured during the first reversible cycle. Values for the second increase in strain were slightly higher.

Figs. 7 and 8 show log-log plots of the maximum pinning force as a function of upper critical field for the unHIP'ed and HIP'ed wires respectively. The data in Figs. 7 and 8 have been fitted to lines of best fit. For both samples, the two halves of the first strain cycle and the increase in strain data from the second cycle have been fitted separately as well as the average of all the data.

V. DISCUSSION

The strains at which the critical current is maximum (ϵ_m) for both unHIP'ed and HIP'ed wires are very similar, having values 0.23% and 0.27%. These compare favourably with

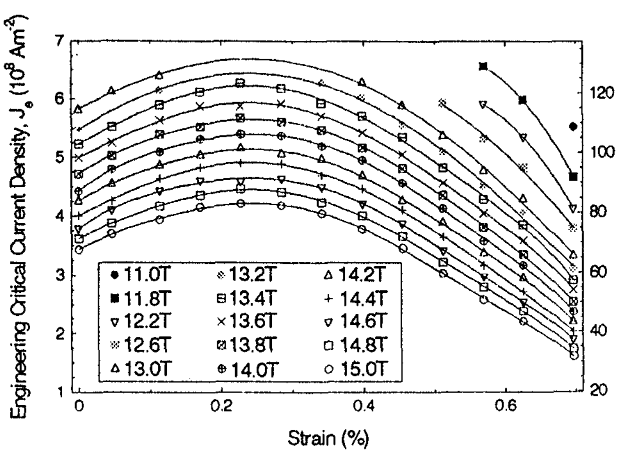

Fig. 1. Engineering critical current density as a function of strain and applied magnetic field for the unHIP'ed wire. Measurements were taken during the second increase of strain.

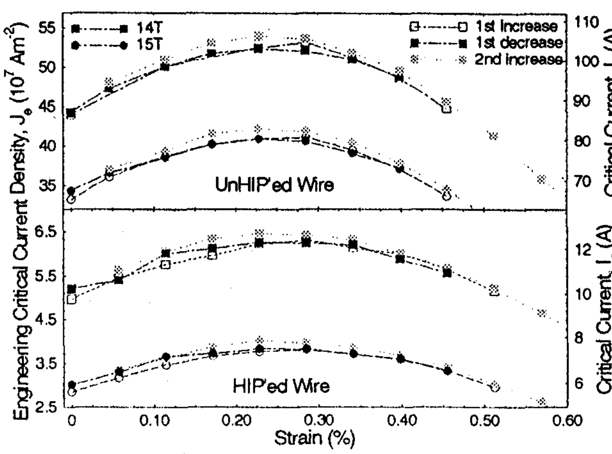

Fig. 3. Engineering critical current density as a function of strain for the HIP'ed and unHIP'ed wires. The data characterise the reversibility in J_e at 14T and 15T.

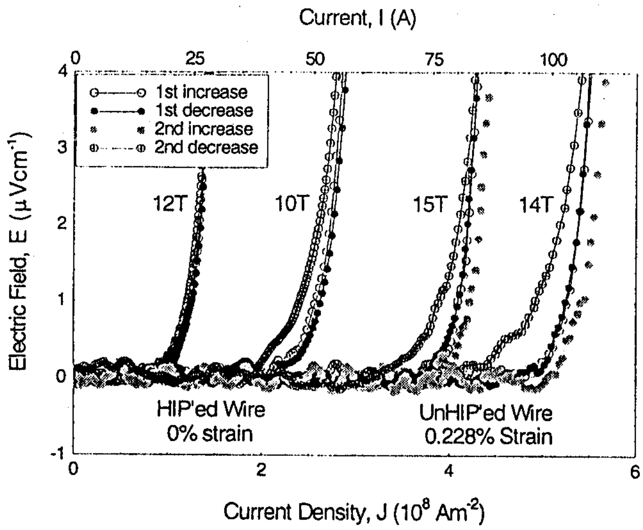

Fig. 4. Electric field-current density characteristics for the HIP'ed and unHIP'ed wires at the same strain for a given field during different strain cycles.

values reported in the VAMAS report of 0.2% and 0.21% for an internal tin wire measured at two independent laboratories [8]. The value of ϵ_m remains constant for both wires regardless of whether the strain is increased or decreased, and is reproducible on the second increase of strain.

The increase in critical current density with the second increase of strain can be attributed to the composite nature of the wire. When straining the wire, some components deform plastically while others remain elastic. Thus, on returning to zero strain, the strain state for the wire may be changed from the original state causing a change in the critical current.

The electric field-current density characteristics give more direct evidence as to the irreversibility of the wires. The first increase and decrease of strain show that the critical current is reversible, no matter what electric field criterion is used. The increase in critical current observed on the second increase in strain is found irrespective of criterion used. The degradation of critical current with the second decrease of strain is a dependent on criterion. A smaller criterion leads to a larger difference between that critical current observed and

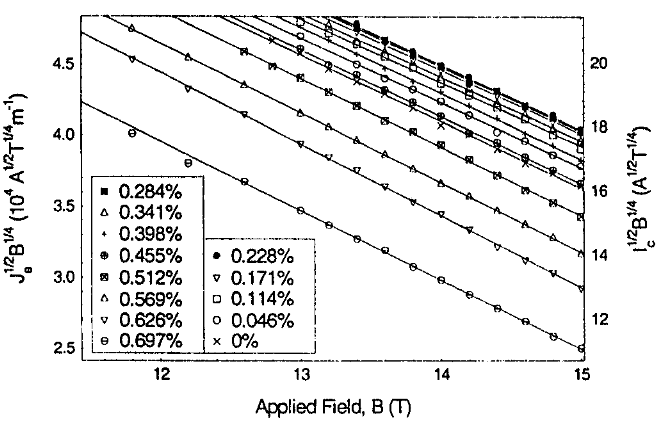

Fig. 5. Kramer plot for the unHIP'ed wire, from which B_{c2}^* and $F_{p\text{-max}}$ are calculated. The data were taken during the second increase of strain.

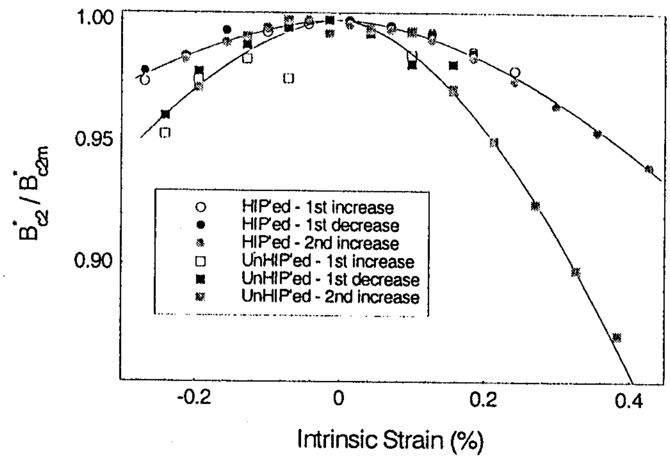

Fig. 6. Reduced upper critical field as a function of intrinsic strain for the HIP'ed and unHIP'ed wires.

that found during the first increase of strain. The index (n) of transition, given by $E = \alpha J^n$, is smaller because there is a resistive region that appears in the trace before the wire goes through the complete superconducting transition. This effect is less apparent at low currents as shown by the 12 T characteristics for the HIP'ed wire that almost overlap. This suggests that after the cycle to 0.7%, the wire was damaged in some way, and this smaller index of transition is due to a transfer current or heating effect. This feature is seen on the characteristics of not only the unHIP'ed wire, but also the HIP'ed wire. By comparing E-J characteristics at 0.63% strain when it was increased to and decreased from 0.7%, a similar change in the index of transition was noted suggesting most of the damage was done above 0.63%. This also suggests that the HIP'ing reaction did not improve the ultimate tensile strain of the wire.

The strain tolerance of the reduced upper critical field for the HIP'ed wire is greater than that of the unHIP'ed wire. The scaling law [4] for B_{c2}^* and the volume pinning force F is:

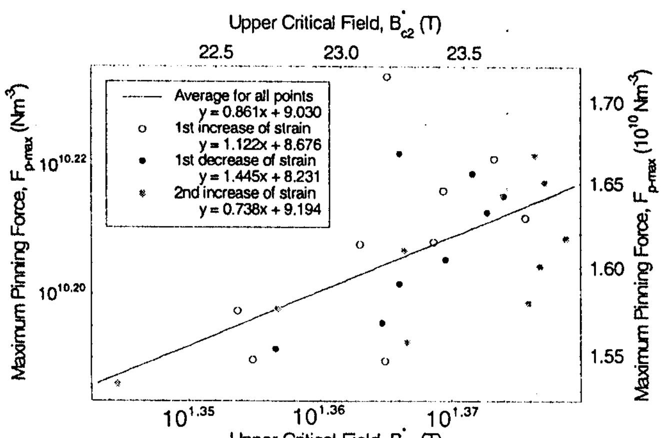

Fig. 7. A log-log plot of the maximum pinning force as a function of upper critical field for the unHIP'ed wire. The equations in the legend give best fits to the data.

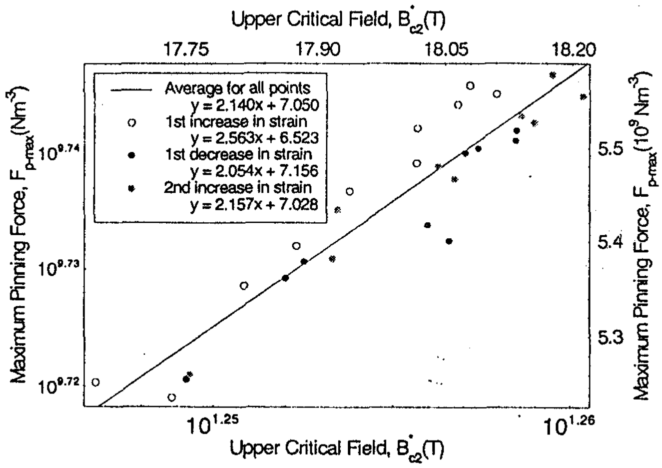

Fig. 8. A log-log plot of the maximum pinning force as a function of upper critical field for the HIP'ed wire. The equations in the legend give best fits to the data.

$$B_{c2}^*(\epsilon) = B_{c2m}^*\left(1-a\left|\epsilon-\epsilon_m\right|^u\right) \quad (1)$$

$$F \propto \left[B_{c2}^*(\epsilon)\right]^m f(b) \quad (2)$$

where B_{c2m}^* is the maximum upper critical field, and f(b) is a function of the reduced critical field only. Using u=1.7 in (1), fits were made to the data shown in Fig. 6. The resulting values for the constant *a* are reported in Table I along with values reported by Ekin [4] for comparison.

As can be seen from Table I, the unHIP'ed sample was more strain sensitive than the samples measured by Ekin. The HIP'ed sample was less strain sensitive.

The reduced sensitivity of the reduced upper critical field to strain is important for improving applications. If the HIP reaction could be optimised so that the critical current density, and upper critical field of the wire remained close to unHIP'ed values, but the tolerance to strain was improved as reported here, further enhancements of wires for high field and large scale applications may be achieved.

Ekin found that variable strain data were parameterised by m = 1 for Nb_3Sn in the scaling law for F. From data in Fig.7, it can be seen that m = 0.861 for the unHIP'ed sample which is in agreement with the data of Ekin. However the HIP'ed sample has m = 2.140. Data obtained at variable temperature lead to typical values for m of between 2 and 3.5. Therefore the value of the m found in the scaling law for the HIP'ed sample is more like the values obtained from variable temperature data. We suggest that the closing of the voids associated with the HIP treatment probably causes this change in m. These results may help provide a more complete description of the scaling law, and the relationship between variable temperature and variable strain data.

TABLE I
STRAIN SCALING LAW PARAMETER COMPARED WITH EKIN'S RESULTS

Sample	a ($\epsilon<\epsilon_m$)	a ($\epsilon>\epsilon_m$)
UnHIP'ed	1126	1640
HIP'ed	530	623
Ekin [4]	900	1250

VI. Conclusions

The critical current density of HIP'ed and unHIP'ed Nb_3Sn Modified Jelly Roll superconducting wires has been measured as a function of magnetic field and strain at 4.2K. The critical current was shown to peak at a maximum strain of 0.23% and 0.27% for the unHIP'ed and HIP'ed wires respectively, in close agreement with the VAMAS report. The critical current was also shown to vary irreversibly with strain for both HIP'ed and unHIP'ed wires, with reversibility only being seen over one cycle in strain. The critical current density and upper critical field of the wire have decreased after HIP'ing. The reduced upper critical field derived from Kramer plots was found to be less strain sensitive for the HIP'ed wire than for the unHIP'ed wire. By considering the maximum pinning force as a function of upper critical field, the form of the scaling law has been evaluated. The index (m) was found to be 0.861 for the unHIP'ed wire which increased to 2.140 for the HIP'ed wire. We suggest this is probably due to the closing of the voids during the HIP reaction.

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