Critical current determination of artificially welded HTS samples by In field Hall Mapping Technique

X. Granados, B. Bozzo, S. Iliescu, E. Bartolomé, T. Puig, X. Obradors, J. Amorós and M.Carrera.

Abstract—**The direct observation of the field at the surface of SC samples when the field is applied or in the remanent state, allows the observation of the current distribution along the magnetization loop by using inverse problem solvers. Furthermore, the mean value of the field reflects well the magnetization of the sample obtaining the magnetization loop taken in account both possibilities, the In Field Hall Mapping technique, thus, has revealed as a powerful characterization technique. This technique can be improved by including the critical state simulation, giving so a very complete way to characterize artificially welded superconducting samples, thus allowing the identification of the critical current flowing through the surface between domains as is the case of the effect of welded bulks. Some examples of the characterization procedures are reported.**

***Index Terms*—superconductors characterization, magnetic remanence currents, superconducting welding.**

I. Introduction

THE great effort devoted to the realization of superconducting welding between ceramic pellets of YBCO has impulsed the development of fast, easy, non destructive and efficient techniques to determine the quality of them. Several techniques have been proposed to watch the quality, but the non destructive requirement restricts them to magnetic testing. Essentially, there are two ways to obtain information about the currents induced in the superconducting sample after a magnetic field is applied, determining so which current is trespassing the superconducting joint, the intergrain current, and the current which is flowing inside the grain, the intragrain current. One way is just to determine the magnetization from integral magnetic measurements done, habitually, in magnetometers. The other way is to observe the local value of the magnetic contribution of the sample during or after the application of an external magnetic field. This last proposal has been strongly developed along the last years by using magneto-optic microscopy or by obtaining the values of the normal field point by point by rastering a Hall probe. In any case, both techniques require the support of an Inverse Problem Solver to obtain the map of currents corresponding to the measured magnetic field map.

Although magneto-optic techniques are more powerful and faster than Hall Scanning Magnetometry, the fact of its non linear behavior reduces the field of application to middle field situation just in the range from some Gauss up to hundreds of Gauss, after a calibration of the system. On the other hand, Hall magnetomery shows very good linearity from tenths of Gauss up to several Tesla. The most relevant counterpart of the Hall Scanning Magnetometry could be the speed of the measurements.

Both local techniques have appeared powerful tools to understand the current distribution generated in a magnetization process and to qualify the effect of local inhomogeneties over the superconducting critical current along magnetization processes.

In this work we study the quality of the welds that we have performed between YBCO blocks by using silver to induce the local fusion [1]. Our characterization method has been developed from the simulation of the current distribution, which can be deduced from the direct application of the Bean model for critical state, in the case of the non homogeneity generated for a weld, and we contrast these results from those obtained the “Caragol” Inverse Problem Solver [2], [3] to the magnetization map, measured by In Field Hall Mapping technique [4], [5] at the remanence state.

II. Experimental

A. Samples

Standard single domain pellets of YBCO have been cut out in order to perform 10x10x5 cm^3 parallelepipedic blocks. Each one has been also cut in order to obtain two 10x5x5 cm^3

Manuscript received October 5, 2004. This work was supported in part by the TMR U.E Contract HPRN-CT-2000-0036 ERBFMRXCT “Supermachines”..

X. Granados is with the ICMAB-CSIC, Campus UAB, 08193 Bellaterra, Spain (e-mail: granados@icmab.es).

B. Bozzo is with the ICMAB-CSIC, Campus UAB, 08193 Bellaterra, Spain (e-mail: bozzo@icmab.es).

S. Iliescu is with the ICMAB-CSIC, Campus UAB, 08193 Bellaterra, Spain (e-mail: iliescu@icmab.es).

T. Puig is with the ICMAB-CSIC, Campus UAB, 08193 Bellaterra, Spain (e-mail: teresa.puig@icmab.es).

X. Obradors is with the ICMAB-CSIC, Campus UAB, 08193 Bellaterra, Spain (e-mail: obradors@icmab.es).

J. Amorós is with the Department of Applied Mathematics of the UPC, Diagonal.647, 08028 Barcelona, Spain (e-mail: jaume.amoros@upc.es).

M. Carrera is with the Department of Medi Ambient I Ciències del sòl of the U de L, Jaume II 69, 25001 Lleida, Spain (e-mail: mcarrera@udl.es).

parts to be welded. Each pair is joint by pressure with a thin foil of silver. The superconducting pair is then heated up near to the silver melting temperature and slowly cooled down, allowing the recrystallization of the joint, as described elsewhere[1].

The 10x10x5 cm^3 welded samples so obtained are subjected to an oxygenation process in the standard way in O_2 atmosphere at 450ºC.

B. *Magnetic measurements*

The contribution of the currents induced in the sample to the perpendicular component to the total magnetic field, habitually called magnetization, has been measured by rastering a Hall probe of 100 x 100 μm^2 over the surface of the samples at a flying distance of 80µm. The measuring grid has a pitch of 160 µm. The measurements have been performed in boiling nitrogen, at normal atmospheric pressure, in between the poles of a magnet, after a field cooled process in a field of 0.6 T. The values reported correspond to the remanence state, after zeroing the applied field.

III. Current distribution SImulation

The inductive currents have been simulated with the help of the software called "Trazacorrientes" [6], [7], [8]. It works on the basis of the Bean critical state assumptions in a 2D symmetry, it means that the applied field is homogeneous in the z axis direction and the current distribution spreads in the xy plane. The simulation assumes that the structure of shielding currents is built up by a set of closed loops of current distributed over a superconducting space. This superconducting space is a *n* x *m* bit map picture of the sample, where each pixel assumes a value according to the state of the corresponding site in the superconducting sample. In the beginning, when the external applied magnetic field (*H*) is zero, the value of each pixel should be 0 or -1, In our simulation 0 means that the site is eligible to transport current of an elemental loop and -1 represents non superconducting parts of the sample such as voids, cracks impurities or any other inhomogeneity which does not allow to carry current. Only 0 sites are available for elementary currents of a loop.

The elementary currents have been selected to be of the same modulus, 1, and can flow in four basic movements, right, left, up or down. For the simulations presented here, we have chosen to work with 100x100 pixel matrices allowing for reasonable quick calculations. In the framework we are working, the current is normalised by the current flowing through a site, $J_c\, ds$, where J_c is the critical current and *ds* is the effective area of the site.

The simulations are made in the assumption of ZFC processes by increasing, in steps of H_{min}, the applied field. When the first step of field is applied, $H= H_{min}$, a loop of current is built starting from the lower most, left most available site, and assigning a current direction just to right. The value assigned to the corresponding pixel is that of the step of field applied, N H_{min}=1H_{min} in this case. Looking for the right most available site, the algorithm moves to that site,

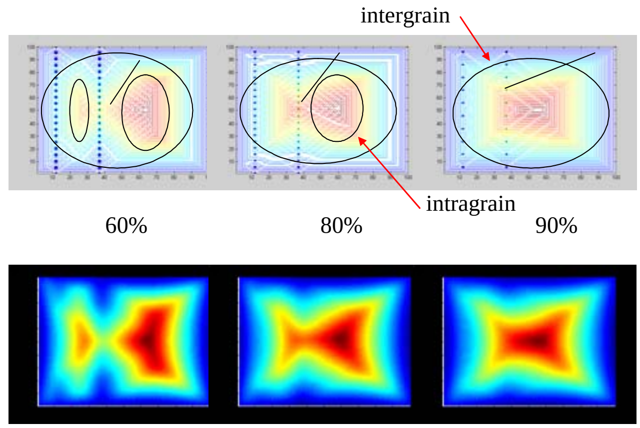

Fig. 1. Up: Simulation of the currents corresponding to a double joint in the case of a critical current ratio, r, of 60%, 80% and 90%. The ellipses show both the intragrain and the intergrain current loops, as the arrows sign. The diminishing of the critical current in the boundary is corresponded with an enhancement of the charge transfer area, which is related with the angle between the current lines and the boundary. Down: The magnetic field generated

assigning a current in the direction which it has moved and the pixel value corresponding to the field step, *N*=1. The "Trazacorrientes" algorithm finishes the loop and looks for a new unconnected loop at the same field. If "Trazacorrientes" finds it, it starts a new loop with the same criterion, assigning the same value to each pixel, and the corresponding current sense. In case a new loop at the same field step is not found, the field is increased one step more, *N* is increased by 1, and the algorithm restarts to work assigning now the pixel value corresponding to the field step done.

In figure 1, we can observe the results obtained by applying this procedure to the pellets described in section I. The results correspond to two welds separating grains with different sizes. The welds represented correspond to intergrain-intragrain currents ratios, *r*, of 60%, 80% and 90%. It can be observed two kinds of induced current loops, those extended to the whole sample and those that cannot extend more than a grain. Looking to the more centred junction, which works as a grain boundary, we can observe that the current lines are directed towards the junction forming an angle characteristic of the ratio, *r*, [6]. The formation of unconnected current loops depends, thus, on both parameters: the size of the grain and the ratio *r*.

Within the simulation procedure we can also calculate the corresponding perpendicular component of the field contribution of the sample. In the figure 1 (down), we have the result corresponding to a thin sheet of a thickness of a hundredth of the length, at a distance of 5 hundredths. The enlargement of the thickness only affects to the curvature of the field isolines; for a very thick sample, the isolines will become straight lines just as the current path lines. Of course, the presence of unconnected loops is corresponded with a peak on the magnetic profile.

For equal sized grains the current map and the corresponding magnetic profile are symmetric, each isolated loop of current is repeated at the same level in the other grain,

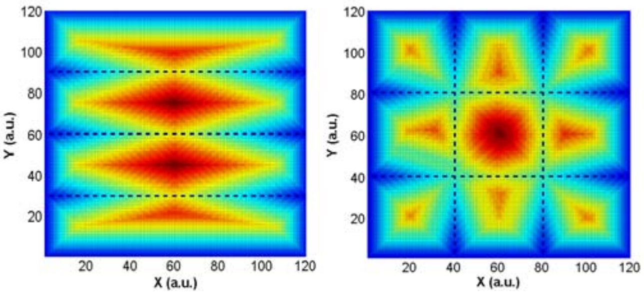

Fig. 2. Current patterns corresponding to two different grain structures. The current ratio *r* is 50%.for every grain boundary. Although in each picture the grains are of the same size, the patterns differ according to the coordination of each grain with the others. Equivalent coordination induces the same pattern of currents

if both intragrain critical currents are the same.

As can be observed in figure 2, the distribution of currents in each grain not only depends on the size and on the current ratio *r* but also depends on the coordination with the grains in the neighbourhood. The only characteristic which is present in all the grain joints is the angle between the current lines and the boundary. In fact, this property reflects the charge conservation law.

IV. Measurement results

In order to determine the joint quality, we choose to use the intergrain-intragrain critical current ratio, *r*. To illustrate the correspondence with the simulations, we have selected two samples with extreme behaviors. Sample A, which clearly separates two peaks, and sample B which clearly shows only one peak in the magnetic map.

In figure 3, both magnetic maps corresponding to samples A (upper left) and B (upper right) can be observed. From the measured values of the z component field, we extract the current distribution corresponding to both samples by using the inverse problem solver "Caragol". The currents are ordered in loops which can be clearly seen in both cases. The

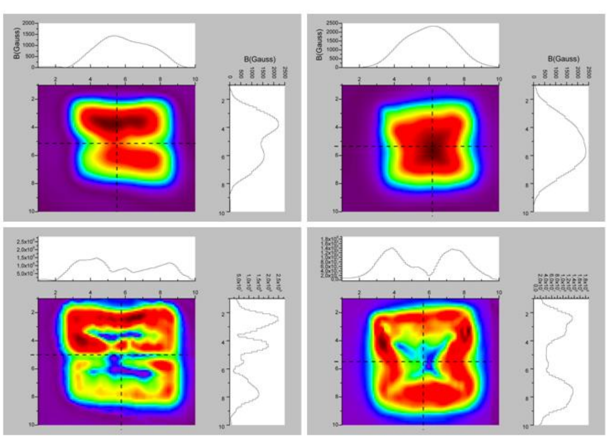

Fig. 3. Magnetic maps corresponding to sample A (upper left) and sample B (upper right). By Inverse Problem calculations ("Caragol") we obtain the distribution of current density modulus, shown below. The junction corresponds to the drawn horizontal line

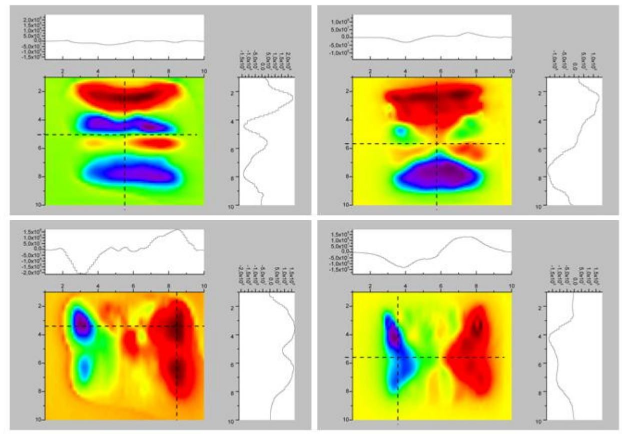

Fig 4. X (up) and Y(down) components of the current density distribution on samples A (left) and B (right). The two current loops on sample A can be clearly seen at the X-current values along the vertical section marked in the figure. The X-component in sample B does not show this behaviour. The current flowing through the weld can be appreciated in the Y-component. The current at the peak is higher than that flowing through the junction in sample A and gets similar values on the sample B. It allows extracting the ratio r

picture corresponding to sample A shows clearly the intragrain loops, and sample B shows only extended loops, associated to the intergrain currents. In both samples we can compare the results with those represented by the simulation in figure 1. We can deduce the intragrain current in each of the two current loops in sample A, and the values of the current in the inner part of the grain in sample B.

A better view of the current distribution can be observed by representing separately both components of the current, that perpendicular to the weld, the Y component, and that parallel to the weld, the X component. In figure 4 we have the results.

As indicated in the figure caption, components X and Y are represented on the upper and lower figures for samples A, on the left, and B on the right. Each figure has at its right side the values corresponding to the cutting line drawn vertically on the current map.

By looking at the X component of sample A we can see clearly the two current loops and, if we consider the central values shown in the curve at the right, the current changes its sign as corresponds to the loop. The current flowing to the right (positive) is greater than that flowing to the left. The difference is just the charge flowing through the junction towards the other grain. In the lower side of the same sample there appears a second loop with different currents going to the right and to the left. The difference now is the current coming from the welded junction. The situation in the sample B is quite different. The current flows through the junction and no loop is observed at the upper and lower grains.

Looking now at the lower pictures of figure 4, where the Y component of the currents is shown, we can observe the flux of current through the junction, whereas at the center of the sample the current Y-component is zero. The pictures showing the X and Y components of the current show clearly that the current is flowing as in the simulations shown in figure 1.

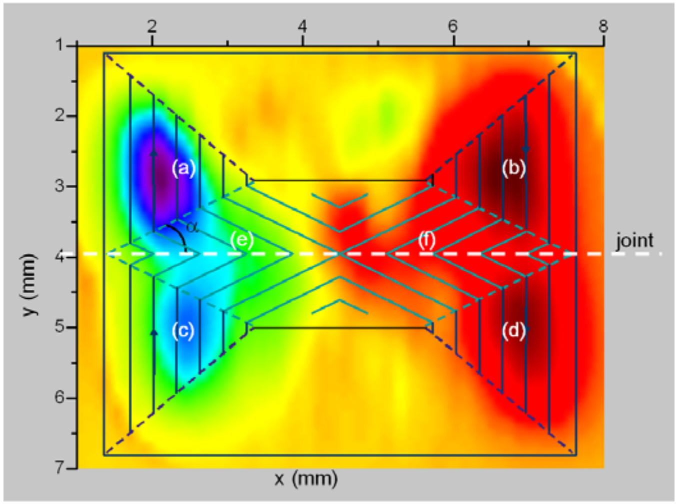

Fig. 5. The Y-component of the current in sample A is overlapped with the figure of currents which is obtained from the simulation. It is clear the presence of two loops of current, over the weld and below it. The extreme values a, c and b, d correspond to the regions where the current flows in the Y direction downwards and upwards respectively.

In figure 5, we can observe the overlapping between the Y current figure of sample A and the sketch of currents deduced from the simulation. The extreme values correspond to the zones where the current is flowing in the Y axis direction. In these zones the current density is just the intragrain critical current, whereas the current density in the joint line is just the current flowing through the weld, so is the intergrain current.

From the values in the regions of that picture we can extract the values of both the intragrain and intergrain critical current densities, and hence the ratio *r* which measures the weld quality.

As we can deduce from the simulations, the system is very sensitive for the detection of the current values when the current ratio is higher than a 50%. Lower values introduce more imprecise results.

The efficiency of that method to measure *r* is also related with the possibility to reproduce the standard current pattern. It is well accomplished if there are no other defects in the sample which can disturb the postulated geometry of two rectangles. Any defect or inhomogeneity in the grains, with a size large enough to disturb the geometry, does not allow distinguishing between both currents and then the quality ratio cannot be inferred.

In Table I, the values of the corresponding current densities for samples A and B are shown.

V. Conclusion

In summary, we can deduce from simulations made within the Bean model assumptions, the meaningful values of the current pattern obtained by the Inverse Problem solvers, applied over the map of the Z-component of the magnetic field. In the case of welds made in between YBCO pieces of good quality, we can extract the ratio between the critical currents flowing through the welds and those characteristic of the sample. The values of the component of the current perpendicular to the weld in the maximum and in the weld

TABLE I
Current values obtained

Sample	Maximum intergrain current density	Maximum intragrain current density	Ratio
A	1.4 x10^4 A/cm^2	2 x10^4 A/cm^2	0.7
B	1.62 x10^4 A/cm^2	1.69 x10^4 A/cm^2	0.96

allow obtaining the quality ratio, *r*, between the critical intergrain and intragrain currents.

This non destructive analysis allows a fast characterization of welds and other similar inhomogeneities.

References

[1] S. Iliescu , X. Granados, E. Bartolome, S. Sena, A.E. Carrillo, T. Puig, X. Obradors, J. Evets, "High critical current YBCO artificial joints using Ag foils as welding agent" Supercond. Sci. Tecnol, 182-185 (2004).

[2] On line at: www.jaumetor.upc.es

[3] M. Carrera, J. Amorós, X. Obradors and J. Fontcuberta, Supercond. Sci Technol **16**, 1187-(2003),

[4] S. Iliescu, S. Sena, X. Granados, E. Bartolomé, T. Puig, X.Obradors, M. Carrera, J. Amorós, S. Krakunovska and T. Habisreuther, IEEE Trans . Appl. Supercond, **13**, , 3136 (2003).

[5] X. Granados, S. Sena, E. Bartolomé, T. Puig , X. Obradors, M. Carrera, J. Amorós, H. Claus, IEEE trans. Appl. Supercono. 13, 3667 (2003)

[6] X. Granados, E. Bartolome, B. Bozzo, T. Puig and X. Obradors. "Simulation of the current distribution in non homogeneous superconducting systems", in preparation

[7] X. Granados, E. Bartolomé, B. Bozzo, T. Puig, X. Obradors. "Simulation of the Distribution of Currents in non-homogeneous Superconducting Systems". VII EFFORT Meeting, Ed D. Cardwell, Cambridge (2004)

[8] E. Bartolomé, X. Granados, T. Puig, X. Obradors, E. S. Reddy and S. Krakunovska, "Critical State of YBCO Superconductors with artificially patterned holes", this conference