A Model for the percolation effect in the magnetic susceptibility of HTSC composites

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ABSTRACT: A simple model is proposed to explain the nature of the screening properties of superconducting composites. The percolation effect in the susceptibility and the maximum in shielding efficiency are interpreted as a consequence of the encapsulation of non-superconducting areas by superconducting material. A three dimensional simulation based on site-bond percolation theory was conducted to test this model, using the calculated fraction of bonds that become superconducting at low temperature.

1.   INTRODUCTION:

Improving the mechanical properties of high temperature superconductors (HTSC) by adding reinforcing material could promote the application of bulk material, on the condition that there is no severe reduction in superconducting properties. In this context we proposed a model for the variation of the screening properties with composition of superconducting composites.

2.   MODEL:

Bruneel et al. (1998) illustrated that the susceptibility of a composite of Bi-based superconductor with MgO shows a temperature dependent percolation effect around 20-40 vol% superconducting phase, at the same concentrations the screening efficiency exhibits a maximum. Fig. 1 and Fig. 2 illustrate these phenomena. Comparable effects were obtained by Dubois (1995), Landinez Tellez (1999) and by McLachlan (1994) for NbC composites with KCl.
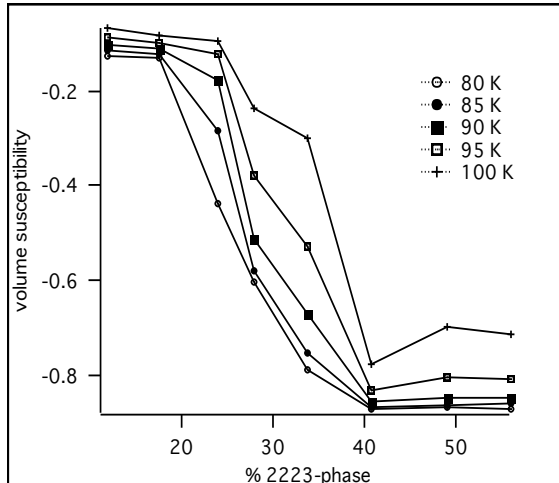
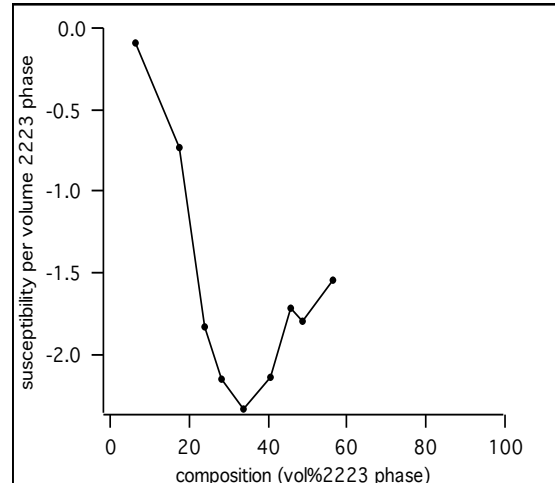Fig. 1: AC susceptibility in function of composition for HTSC-MgO composites

Fig. 2: Susceptibility per volume superconducting phase for HTSC-MgO composites as a function of composition at 80K.

These phenomena can be explained within the following model. We consider that, with increasing amount of superconductor, three possible mechanisms can occur, as is illustrated in a 2 dimensional outline in fig. 3:

a) The added superconducting material is isolated from other superconducting domains by a non-superconducting matrix and contributes to the total susceptibility of the sample, according its own volume.

b) The added superconducting grains form the 'missing link' required to shield a certain inner-volume. In this case the whole shielded volume will contribute to the susceptibility.

c) The new superconducting material ends up inside an already shielded volume; in this case the total susceptibility of the sample will not change upon the addition of superconducting material.
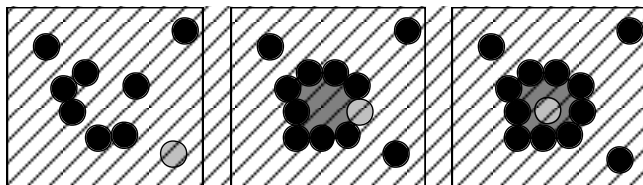

Fig. 3: 2-Dimensional outline

Each of the three possibilities can occur at any concentration; but the statistical probability to occur is determined by the amount of superconducting material already present.

The results can be understood as follows: at low concentrations, the added material will be isolated and the susceptibility of the sample increases in proportion to its own volume. With increasing concentrations the probability of encapsulating a volume of non-superconducting material raises. The susceptibility of the specimen increases proportionally to the shielded area, so the efficiency of the added grains is much increased, we call them 'super-efficient'. For higher concentrations, the volume of the composite will be almost completely shielded. The probability for an added grain to encapsulate a non-shielded area decreases. New material will most likely end up in a region that was already shielded; consequently the total susceptibility of the specimen will not change. If the grain ends up on the outside of a shielded area, it will contribute to the total susceptibility according its own volume. In both cases the susceptibility per volume 2223 phase in

the composite will decrease, because the relative amount of 'super-efficient' grains decreases. This can be seen in figure 2.

3. SIMULATION:

We simulate this process in a three dimensional lattice, focussing on the site bond problem, where sites are connected to each other if they are both occupied and if they are connected through a path of occupied sites and bonds.

The fraction of superconducting bonds present in the samples was established from resistivity measurements. The room temperature isolator-conductor percolation is experimentally determined to be at approximately 13% conducting phase. This value is quite close to the percolation threshold for the cubic lattice with next nearest neighbours ($p_S^C = 13.7\%$). However, from measurements of the resistivity as a function of temperature we see that for transition to zero resistivity the percolation threshold rises up to 24% of superconducting phase. This suggests that at low temperatures not all the electrical bonds between neighbouring superconducting grains became superconductive themselves.
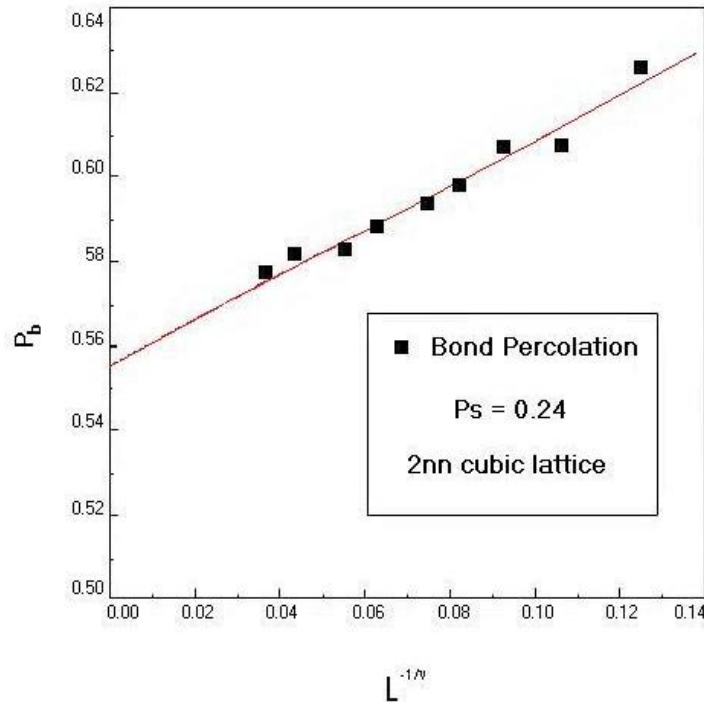

Fig. 4: Finite size scaling plot for the site-bond percolation model with p_s=0,24.

We use a three-dimensional cubic lattice of $L \times L \times L$ sites with each site being occupied with probability p_s and each bond with probability p_c. We fixed the probability p_s=0,24 according with the experimental results and then we look for the fraction of bonds needed to have the spanning cluster. Since the lattices prepared with the computer are finite in size we have to use finite size scaling to determine the percolation threshold on an infinite system. According to Stauffer (1992) the percolation threshold for finite size system depends of the value of L. The average threshold for a lattice of size L, at a fixed value of p, approaches the true value according with the scaling law:

$$p_B^{AV} - p_B^C \sim L^{-1/\upsilon}$$

Where ν is a critical exponent of the correlation length that diverges at p_c. The root mean square deviation (rms.) of the threshold also scales with system size. Using the scaling law stated above and taking the universal and exact value ν=4/3 we can extrapolate the percolation threshold for the infinite lattice. We plot the calculated thresholds p_B^{AV} versus $L^{-1/\nu}$ and extrapolate to the interception by letting $L \rightarrow \infty$. In our calculations different values of L (L=16,20,24,28,32,36,48,64 and 80) were used to obtain a good statistical accuracy. The value found, as is illustrated in fig. 4, for the fraction of bonds that become supercon-ducting when cooled down is $p_B^C = 0{,}5558 \pm 0{,}0027$.

To model the magnetic susceptibility we calculated the total fraction of empty sites that become isolated from the outside of the volume. The total magnetic susceptibility of the sample will be proportional to the number of superconducting grains plus the volume of non-superconducting material that is entrapped into the superconducting phase and is not in contact with the outside through a non-superconducting path. Figure 5 shows the susceptibility per volume as a function of the fraction of superconducting material in the volume. No scaling was done and the largest size of the system compatible with the computer resources available was used, L=128 and the properties were calculated after 20000 simulations,.
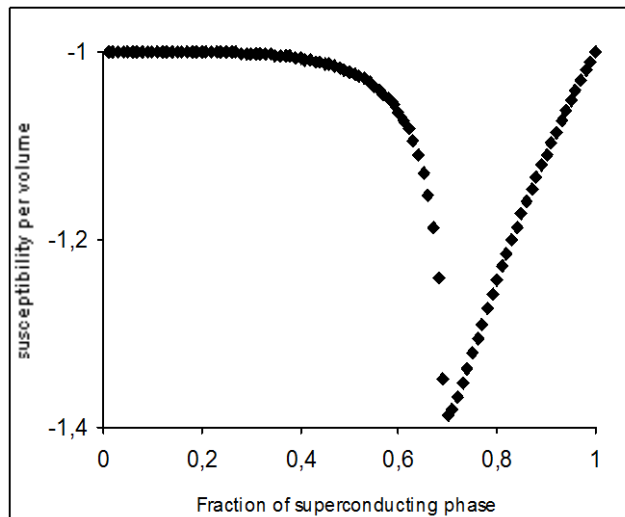

Fig. 5: Simulation of the susceptibility per volume superconducting phase.

4.   DISCUSSION AND CONCLUSIONS:

The correlation between susceptibility and composition is explained in terms of random distribution of superconducting and non-superconducting phases and the occurrence of intergrain coupling effects. We tested these assumptions using a simple three-dimensional percolation model and we found that it properly describes all the major features of the observed relationships.

Remaining discrepancies can undoubtedly be attributed to the lack of detail in the geometry of the model used here and the unaccounted occurrence of demagnetisation effects. In addition, A discrepancy between measurement and calculation in the low concentration region of the susceptibility per volume HTSC is expected to be related to the effect of the penetration depth.

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