THE ANGULAR DEPENDENCE OF CRITICAL CURRENTS IN Nb₃Sn – EFFECT OF SOME PREPARATION CONDITIONS

II. THEORETICAL CALCULATIONS

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By considering some columnar parts in the superconducting grains, we explain some characteristic features in the angular dependence of the critical currents of Nb₃Sn tapes, prepared in the presence of additional impurities in the reaction atmosphere of the vapour deposition process. Mainly, the decrease of the critical current in magnetic fields nearly parallel to the tape surface (which appears in the form of a “valley” in the polar diagram of the critical current) can be explained by these considerations. By comparing the theoretical and experimental results, including structural investigations, the most probable shape of the grains is suggested.

1. INTRODUCTION

Although the precise pinning mechanism in Nb₃Sn is not yet known with certainty, generally it is assumed that the pinning on grain boundaries is the determining effect which causes the relatively high critical current density values both in diffusion processed and vapour deposited Nb₃Sn tapes. This fact is roughly indicated by increasing the critical currents in superconductors consisting of finer grains [1]. Although in some cases additional defects or defect structures arise by addition of some impurities or other phases (as for instance linear defects caused by doping the reaction atmosphere with carbon [2] for chemical vapour deposited tapes, or precipitations in the case of Zr for diffusion processed tapes [3]), the pinning on grain boundaries (or on the boundaries of subgrains) remains the most significant among the other pinning mechanisms.

Actually, the pinning on grain boundaries can be caused by simple surface effect (some modified kind of the surface pinning [4, 5]), but also by the strong anisotropy of the energy gap in Nb₃Sn or other superconductor with A-15 structure. As the crystallographic orientation of neighbouring grains is generally different, the flux lines (having the direction of the magnetic field) will have different energies in these grains. Therefore, one of the grains will attract the flux lines being in the vicinity of the boundary, the other grain will repel them. The magnitude of this interaction (more precisely, it is the so-called \( \Delta \kappa \)-interaction) seems to be sufficient to explain the relatively high critical current densities in Nb₃Sn [6].

Which of these two interactions is more important for the material considered, is not yet clear. However, we could expect that the surface effect could be smaller in superconductors with “narrow” boundaries, and more important for “extended” boundaries between the neighbouring grains.

In the following, we restrict our considerations to the case where the boundary between the grains is isotropic (we give a brief comment on anisotropic boundaries in the Discussion), therefore the main characteristic parameter of the pinning by changing the direction of the magnetic field and/or the current (or generally the Lorentz force) is the shape of the individual grains [5, 7].

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2. CALCULATION OF THE VOLUME PINNING FORCE

Our previous calculations [5, 7] of the angular dependence of the volume pinning force were confirmed by the experimental results of the angular dependence of critical currents in transverse magnetic fields [5, 8], as well as structural investigations [8] of both diffusion processed and vapour deposited Nb₃Sn tapes. In these calculations, such types of the grain shapes were considered, which are also thermodynamically probable (one of the most important facts will be possibly the filling coefficient of the plane — or the volume — with these shapes [5, 7]).

But, as mentioned in the preceding paper [9], some additional impurities in the reaction atmosphere can influence in a substantial way the dimensions and the shapes of the Nb₃Sn grains.

If the density of the nuclei, on which the grains grow, will be relatively large, the neighbouring grains will “interact” (i.e. hinder each other) soon after the grain growth has started. The large increase of the critical current in magnetic fields perpendicular to the tape is mainly caused by the increase of the nucleation centre density in the case that there are some impurities in the reaction atmosphere (these impurities prevent the formation of larger grains and enable the formation of new grains).

Thus, soon after the beginning of the grain formation, the rise of the grains is “restricted” by the presence of neighbouring grains. The result of this interference will be that in the middle part of the grains some columnar parts can occur (in the direction perpendicular to the tape).

These columnar parts change substantially the angular dependence of the elementary interaction force between the boundary and the flux lines and the volume pinning force, too [10].

The changes in the volume pinning force are the largest for those angles where these columnar parts contribute most to the angular dependence of the pinning. As we shall see later, this happens in magnetic fields nearly parallel to the tape surface.

\[ \text{Fig. 1. Different presumed characteristic grain shapes for the calculation of the pinning force.} \]
\[ a - \text{ellipsoidal, } b, c - \text{sinusoidal.} \]

In our calculations of the angular dependence of the volume pinning force \( F_p \), we combine these columnar parts with the characteristic grain shapes used previously [5, 7], as given in Figs 1(a, b, c).

The notations are the same as previously [5, 7], i.e. \( a, b \) are the semi-axes of the ellipse, or the period and amplitude of the sinus, respectively. These shapes represent the characteristic cross-sections of the grains perpendicular to the direction of the current. The dimension of the columnar part is \( A \).