Introduction

The tempting idea of using superconductors to produce strong magnetic fields arose soon after the discovery of superconductivity, but could not be implemented for a long time. It was found that the critical magnetic field of the pure metals in which superconductivity was initially studied did not exceed 0.2 T.

The situation changed radically for the better in the late fifties and early sixties, following the discovery of *hard superconductors*, e.g., Nb–Ti and Nb–Zr alloys with different composition, Nb_3Sn compounds, and so on. Small solenoids manufactured from these materials were used to generate magnetic fields of up to 10 T. Very high critical current densities were reached (up to 10^9-10^{10} A/m^2) after special thermomechanical treatment, but this introduced defects into the hard superconductors.

These results evoked some optimism and it seemed at the time that the main obstacles to the practical utilization of superconductivity had been overcome. However, studies of hard superconductors with high critical-current densities soon revealed the phenomenon of thermomagnetic instability, which was seen as an abrupt change in the magnetic flux in a superconductor, with a characteristic time constant of $10^{-4} - 10^{-6}$ s. Naturally, the process was accompanied by an intensive heat release and, as a rule, returned the medium to its normal state. Even small perturbations of temperature and magnetic field were found to be capable of initiating the thermomagnetic instability. Moreover, this was practically independent of the method of cooling because hard superconductors have a relatively low thermal conductivity, i.e., heat transfer is relatively ineffective. Subsequent studies showed that the thermomagnetic instability could be prevented by ensuring that the transverse size of the conductor (e.g., the radius of a wire or the thickness of a layer) was less than a critical value (usually of the order of 10^{-4} m).

However, it became clear later that this was still not the complete solution of the problem. Actually, these superconductors are not 'good metals' above the critical temperature, e.g., their thermal and electrical conductivities are lower by three or four orders of magnitude than those of copper. Hence, if a region of normal phase appears fortuitously in the conductor close to the critical current density, the Joule heat release in the normal region will be very high. Indeed, it will sometimes be so high that it will actually melt the conductor with a transverse size of $10^{-5} - 10^{-6}$ m. This can be avoided by coating the hard superconductor with a metal having high thermal and electrical conductivities. This coating shunts regions in which the transition to the normal state has taken place and at the same time promotes effective heat transfer. This ensures that, even for equal superconductor and metal thicknesses, the specific Joule heat release is reduced by between two and four orders of magnitude. This usually suffices to stabilize the superconducting state with respect to the effect of random heat sources that initiate normal-phase regions.

It follows that hard superconductors can be used with high current densities to produce,for example, strong magnetic fields, but only if they are in the form of very thin filaments or layers. They then lack the necessary strength, and the large number of crystal defects means that they do not have the required plasticity. The natural and, indeed, the only, way out of this dilemma is to use superconducting composites in which a hard superconductor and a normal metal are in thermal and electrical contact with each other and are combined in a single whole. The configuration of components in such materials depends on their function; it can be very complex and assume a variety of forms. Existing structures include multifilament composites in which a regular structure of superconducting filaments is imbedded in a normal-metal host; film composites consisting of alternate layers of normal metal and superconductor,; and *insitu* composites in which highly elongated superconducting ‘needles’ form a disordered grid in a normal-metal host.

Composite superconductors offer the solution to a wide range of problems, the principal of which are: thermomagnetic instability, instability of the superconducting state with respect to strong pulsed perturbations, heat release under varying external conditions, and inadequate strength and plasticity. It is important to note that the optimum composite superconductor must often satisfy conflicting demands. Thus, the superconducting state must be stabilized by increasing the relative concentration of the normal metal, in which case the current density averaged over the wire cross section may fall well below its critical value. A host with high electrical conductivity will then suppress the thermomagnetic instability, but will give rise to a higher specific heat release in variable magnetic field, and so on. For all these reasons, the structure of a composite is always a compromise that is achieved by a suitable choice of the hard superconductor, hosts with high and low resistivity components, thin filaments twisted around the wire axis, and so on. The electromagnetic, thermal, and mechanical processes in composite superconductors are intimately related because the current–voltage characteristic of a hard superconductor is very dependent on temperature, magnetic field, and – frequently – the deformation. Theoretical and experimental studies of the electrodynamics and low-temperature mechanics of a complex heterogeneous anisotropic nonlinear medium such as a superconducting composite are virtually impossible at the level of its individual structure elements. Moreover, we are usually interested only in the mean temperature, electric field, current density, magnetic induction, mechanical stress and strain, and so on. The situation is typical of heterogeneous media for which it is natural to pass from 'microscopic' to macroscopic description. The superconducting composite is then looked upon as an anisotropic homogeneous medium with effective parameters determined by averaging the parameters of the hard superconductor and the normal host over regions containing a large number of composite structure elements (filaments, layers, fibers, and so on).

The macroscopic properties of composite superconductors, and the processes that occur in them, are studied in the rapidly developing subject of the physics of composite superconductors. This monograph is an attempt to present a unified account of the subject.

Chapter 1 gives a brief review of information on hard superconductors, which is exploited in subsequent chapters. Particular attention is devoted to the critical state, the viscous flow of magnetic flux, and the nonlinearity of the current-voltage characteristic in weak electric fields.

Chapter 2 describes the most commonly used composites and their typical characteristics. The word 'typical' must be treated with caution because advances in fabrication technology and in the properties of hard superconductors, which have a direct bearing on the properties of composites, are constantly being reported. Chapter 2 surveys the thermal, electrical, and mechanical properties of the most frequently employed hard superconductors (Nb–Ti and Nb_3Sn), and of copper and aluminum.

Chapter 3 is devoted to dissipation processes in composite superconductors in varying magnetic fields. Hysteretic losses in hard superconductors and in twisted multifilament superconducting composites are considered. Dissipation processes in filamentary composite superconductors are discussed.

Chapter 4 deals with the stability of the superconducting state in hard and composite superconductors. The thermomechanical instability of low-temperature plastic flow of metals, and the related problem of training of superconducting composites are also discussed. Considerable attention is given to calculations of the current-carrying capacity of composite superconductors.

Chapter 5 examines nonlinear thermal phenomena in superconducting composites carrying a transport current. The propagation and localization of the normal zone in superconductors are reviewed. The current-voltage characteristics of composites and hysteretic effects due to Joule heating are reviewed. The superconducting to normal transition initiated by thermal disturbances is analyzed together with normal-zone propagation in composites with high contact resistance between the superconductor proper and the normal host metal.

Chapter 6 gives a brief summary of high-temperature superconductivity, including the basic properties of high–T_c superconductors that will be needed for the evaluation of advanced superconducting materials.