VI. KRITISKA STRÖMMAR, PRAKTISKA SUPRALEDARE

De tre kritiska storheterna: temperatur, fältstyrka och strömtäthet står i beroende till varandra. Här diskuterar vi kortfattat kritiska strömmens fältberoende. Liksom för fältberoendet, så är kritiska strömmens uppförande beroende av om materialet är typ I eller typ II. Kritiska strömtätheter upp emot 10^7 A/cm^2 har uppmätts. Vi återkommer till kritiska strömmar i samband med Josephson-övergångar - i dessa kan i_c varieras mellan ca 1 och 10^5 A/cm^2.

Vi kan beräkna kritiska strömtätheten på två sätt. Antingen kan vi säga att $i = i_i + i_H$, summan av transport- och skärmströmmar, och säga att supraledningen bryter samman, då $i > i_c$ där i_c relateras till en kritisk hastighet v_c. Denna fås genom att sätta kinetiska energin lika med energigapet, vilket kan beräknas ur BCS-teorin. Eller också kan vi beräkna fältbidraget från transportströmmen och tillsammans med det inducerade fältet ger det ett fält som får jämföras med det kritiska fältet.

VI.1. Kritisk ström i tråd

En ström I genom en tråd med radien R ger fältet vid ytan

$$H_I = I/2\pi R$$

Utan externt fält fås då $I_C = 2\pi RH_c$.

Med externa fältet H_a längs tråden får vi addera detta och eftersom de två fälten är vinkelräta mot varandra ger vektorell addition att

$$H_c^2 = H_a^2 + (I_c/2\pi R)^2$$

Vanligare är att H_a är vinkelrät mot I (ström i magnetspole). Med hänsyn till demagnetiseringsfaktorn för cylinder fås

$$H_c = 2H_a + I_c/2\pi R$$

De två fallen illustreras i figur VI.1. Den kritiska strömmen i en typ I supraledare definieras som strömmen där resistans uppkommer, ej värdet då hela den normala resistansen är återställd.

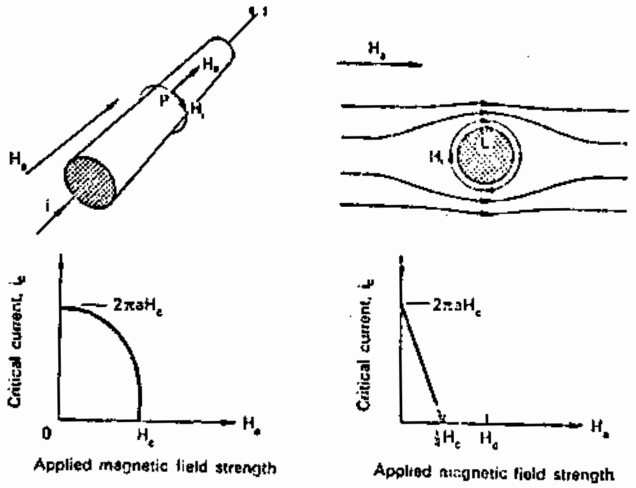


FIG. VI.1. Variation of critical current with applied magnetic field strength. (a) Longitudinal applied field. (b) Transverse applied field (transport current flowing into page).

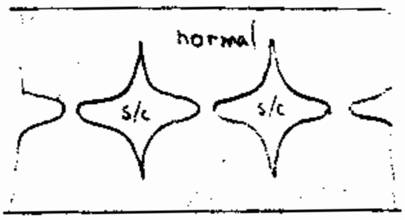


Fig. V.2 *Snitt genom cylindrisk tråd med $I > I_c$.*

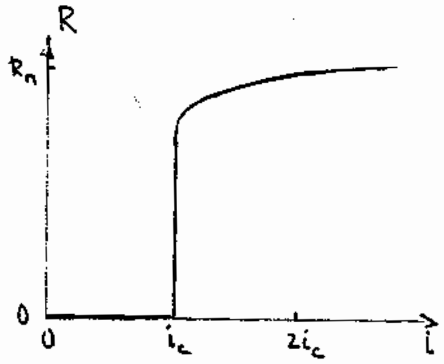


Fig. V.3 *Återställandet av resistansen medelst ström.*

VI.2. Intermediärt tillstånd orsakat av ström

Resistansen ökar inom ett avsevärt strömintervall ovanför I_c. På samma sätt som ett intermediärt tillstånd uppträder i en typ I supraledare ovanför $H_c(1-D)^{-1}$, så finns det också ett intermediärt tillstånd i en strömgenomfluten supraledare. Antag att kritiska fältet uppnås vid ytan vid en kritisk ström. Skulle ett lager då gå normalt, så skulle fältet bli än större vid ytan av den mindre supraledande cylindern och den supraledande kärnan skulle snabbt krympa till obefintlighet. Istället får man alternerande normala och supraledande områden liknande situationen i figur V.2, som beräknats för ett idealt fall. Resistansen ökar snabbt vid i_c men återtar ej normalvärdet förrän i_c överskridits avsevärt.

VI.3. Termisk propagation av normalt område

Går någon del av den strömgenomflutna supraledaren normal, t ex vid en inhomogenitet, så fås värmeutveckling i den punkten. Är värmeavledningen lägre än den utvecklade effekten kommer det normala området att spridas.

I en praktisk supraledande ledare bäddas många supraledande trådar in i en god normalledare, som förmår leda av värme väl och shunta en ev. normal region medan den återgår till det supraledande tillståndet efter en momentan överbelastning.

VI.4. Kritisk ström för typ II supraledare

Vid H_{c1} går supraledaren in i det blandade tillståndet. Flödesrör som rör sig genom supraledaren ger upphov till en emk. Vi bortser emellertid från denna resistans, om den är liten nog, vid definitionen av kritisk ström. Definitionen av kritisk ström i en typ II supraledare blir något godtycklig, då den beror på vad man anser vara en tolerabel eller mätbar, inducerad spänning. Värdet blir relativt lågt i det blandade tillståndet om typ II-supraledaren är perfekt. För en verklig supraledare finns dock inhomogeneiteter, som förmår låsa flödesrör. Därigenom kan man uppnå höga strömtätheter. Ett exempel ges i figur VI.4.

VI.5. Praktiska högfältssupraledare

Det var först i början av 60-talet, som man upptäckte supraledare med höga värden på T_c, H_c och i_c. De båda senare egenskaperna har hög teknologisk betydelse - det gäller inte bara att optimera T_c. H_c och i_c beror i hög grad på den metallurgiska behandlingen. Kallbearbetning med efterföljande värmebehandling, fasurskiljning, martensitiska fasomvandlingar vid låg temperatur osv är av betydelse. Flöden fryses fast av sådana supraledare. Hysteres ger växelströmförluster. Supraledande tråd kan "tränas" - efter ett antal normaldrivningar kan H_c öka.

Mer detaljer ges i den artikel, "High-Field Superconducting Materials" av J.A. Catterall, som

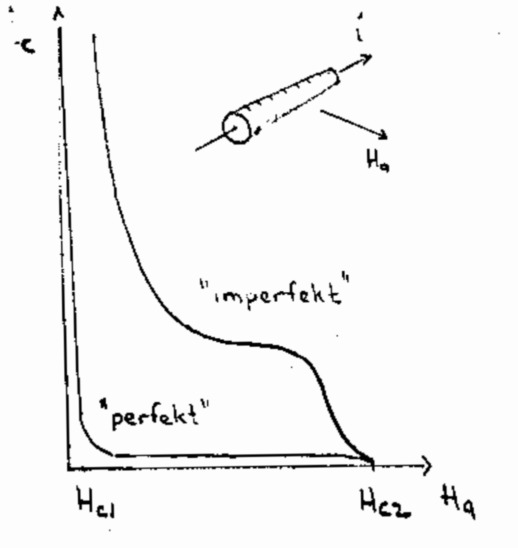
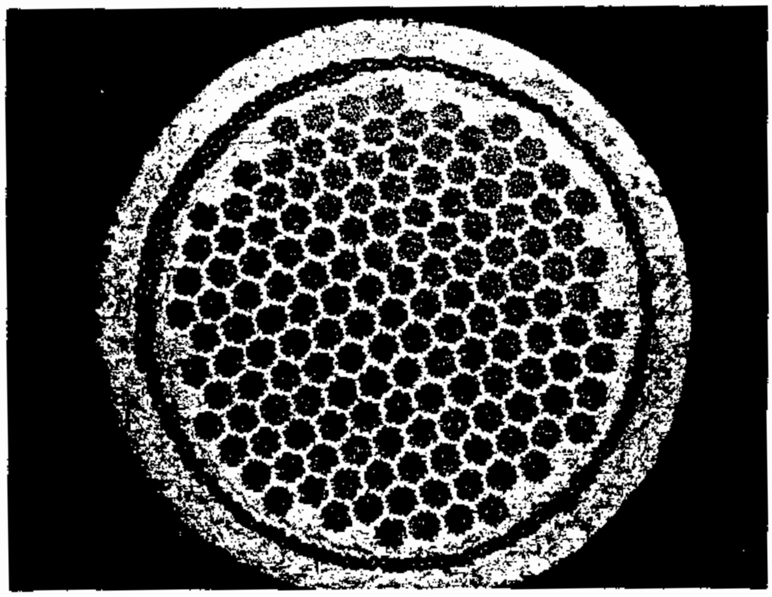


Fig. VI.4 *Kritiska strömmen hos en perfekt och en mindre prefekt typ typ II supraledare (för $T<<T_c$).*

kommer på nästa sida. Men först ett par ord om utvecklingen av tråd för magnetlindningar. Det är vanligt att tillverka tråden i form av ett stort antal supraledande filament inbäddade i koppar. Vridna ("twisted") filament är särskilt motståndskraftiga mot flödeshopp. Nb-Ti-legeringar är vanligast förekommande för applikationer med magnetiska flödestätheter under ca 10 T (100 kG). Över dessa fältstyrkor använder man sig idag huvudsakligen av Nb_3Sn. Det är karakteristiskt för sk A15-supraledare att de är spröda och det är svårt att tillverka tråd, som sedan skall hanteras, t ex böjas vid lindning av magneter. Man har ännu ej lyckats framställa metoder för att praktiskt utnyttja supraledarna med högst T_c. Nb_3Sn kan tillverkas medelst bronsmetoden. Man drar ut Nb trådar som filament inbakade i en bronsmatrix (CuSn). Efter bearbetningen värmebehandlas tråden. Då diffunderar Sn från bronset till Nb som i ett ytskikt övergår till Nb_3Sn. Även V_3Ga och Nb_3Ga har förekommit som kommersiellt framställd tråd.



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2

HIGH-FIELD SUPERCONDUCTING MATERIALS

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The present interest in the prospect of the technological use of superconductivity stems from the period 1960–62, with the discovery by Kunzler[3] at the Bell Telephone Laboratories of the high current carrying-capacity of some of the compounds which Matthias (also of the Bell Laboratories) had discovered previously. Matthias had investigated the critical temperature of a great many alloys and compounds, and the fact that these compounds subsequently proved to have high critical currents and high critical magnetic fields revived the old hope of low-temperature physicists that superconducting solenoid magnets would be capable of generating enormous magnetic fields without the consumption of electrical power. The industrial possibilities for such magnets, and also for machines and cables employing these materials, are dealt with in later chapters.

The materials with which this chapter is concerned are known variously as hard, high-field or Type II superconductors; and henceforth the latter expression will be used.

The realization that superconductors could be divided into two types followed from the theory of superconductivity developed by four Russian workers, Ginzburg, Landau, Abrikosov, and Gorkov (hence the 'GLAG' theory). At the root of this theory is a factor kappa (κ), which depends on certain bulk properties of the material, such as the critical field and the penetration depth. The factor κ is also related to the surface energy of the normal-superconducting interface (mentioned by Dr. Allen in Chapter 1).

The theory shows that superconductors are either Type I, with a positive surface energy, if $\kappa < 1/\sqrt{2}$; or Type II, with a negative surface energy, if $\kappa > 1/\sqrt{2}$. Examples of Type I materials are the elements lead, tin and indium. Examples of Type II materials are the elements niobium and the compounds niobium-tin and vanadium–gallium.

The physical significance of the existence of a negative surface energy in Type II superconductors is that the energy of the superconductor as a whole is lowered by the penetration of a magnetic field, because penetration produces interfaces between normal and superconducting regions, and the interfaces have negative energy. As the externally applied field increases, the flux penetration into Type II superconductors increases. Flux penetration into the material begins at a low value of external field (the lower critical field H_{c1}) and ends with complete flux penetration and the disappearance of superconductivity at a high value of field (the upper critical field H_{c2}).

It is necessary here to discuss the form of the magnetization curves of superconductors, since an understanding of these curves is essential in following descriptions of the properties of superconducting materials. In the well-known relation

CGS-enheter

$$B = H + 4\pi M \qquad 2.1$$

between the flux B inside a material, the external field H and the magnetization M, the magnetic susceptibility k^* is equal to $-1/4\pi$ when $B = 0$. Consequently in a Type I superconductor:

$$-4\pi M = H \text{ when } H < H_c \text{ and}$$
$$-4\pi M \simeq 0 \text{ when } H > H_c$$

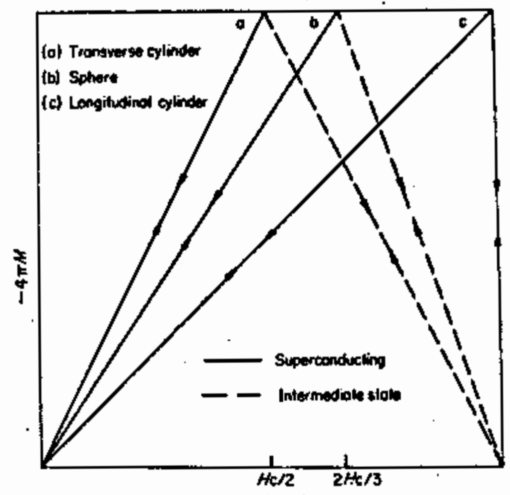

Figure 2.1 Magnetization curves for various shapes of specimen.

$* k = \frac{M}{H}$

where H_c is the critical field. This produces the characteristic triangular magnetization curves shown in Fig. 2.1 (see also Fig. 1.3b). The drop in the magnetization when $H = H_c$ is abrupt only in favourable circumstances, such as in a long thin cylinder parallel to the external field (Fig. 2.1, curve c). For other shapes or configurations the so-called 'demagnetization factor' causes a more gradual flux penetration (Fig. 2.1, curves a and b).

The magnetization curves for Type II superconductors, where $\kappa > 1/\sqrt{2}$, are different since flux penetrates over the field range from H_{c1} to H_{c2} (Fig. 2.2). This figure also illustrates a further property of Type II superconductors, that as κ increases the critical field H_{c2} increases, but H_{c1} decreases.

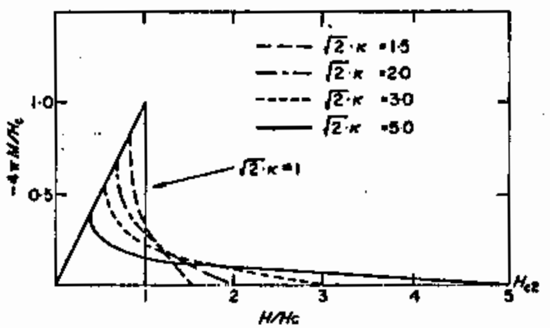

Figure 2.2 Magnetization curves for a Type I superconductor (where $\sqrt{2}\kappa \leq 1$) and for Type II superconductors (where $\sqrt{2}\kappa > 1$).

It is now widely accepted that a Type II superconductor which is situated in an external magnetic field H, where $H_{c1} < H < H_{c2}$, contains magnetic flux. Moreover, this flux is made up of a large number of separate tubes of flux, each tube carrying a very small amount, or quantum, of flux. The tubes lie parallel to the external field, and each tube is screened from the surrounding superconducting region by a circulating current, or current vortex.

The situation is shown diagrammatically in Fig. 1.7, from which it is evident that the tubes take up the form of a regular triangular lattice. The spacing of this lattice depends on the external field, and as the field increases the number of tubes of flux increases, and their spacing decreases, until eventually the tubes overlap at H_{c2}. At this point superconductivity has practically disappeared.

In practice, the curve of $-4\pi M$ versus H is different in increasing fields from that in decreasing fields; or in other words hysteresis is exhibited, as shown in Fig. 2.3. On returning the external field to zero some flux remains trapped within the specimen, resulting in a residual value of M. Nearly complete reversibility of the curves is observed only in specimens that are very pure, fully annealed, and have been very carefully prepared. The magnetic hysteresis in Type II superconductors is caused by the presence of impurities or by various forms of structural defect (such as dislocations and precipitates) in the material. The existence of hysteresis has a vital bearing on the technological properties of the superconductor, as will be shown later in this chapter.

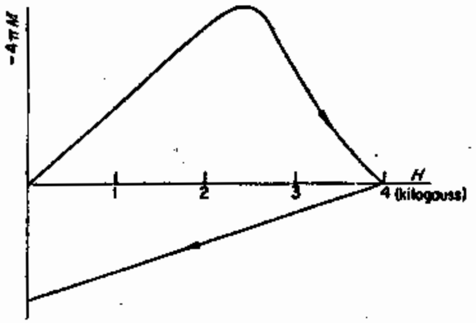

Figure 2.3 **Magnetization curve of cold-drawn niobium wire.**

Type II behaviour can occur in both metals and alloys, and Table 2.1 shows some values of κ, H_{c1} and H_{c2}. The numerical value of κ can be changed by suitable alloying additions, so that Type I material can be converted into Type II. The effect of alloying on κ is given by the relation

$$\kappa = \kappa_0 + (7{\cdot}5 \times 10^{-6}\gamma^{1}\rho) \qquad 2.2$$

where κ_0 is the value in the pure metal, κ that in the alloy, ρ is the normal state resistivity, and γ is dependent on the low-temperature specific heat.

TABLE 2.1 *Type II Superconductors*

Material	T_c, K	κ	H_{c1} (*gauss*) (4.2 K)	H_{c2} (*gauss*) (4.2 K)
Niobium (Nb)	9.3	1.1	1200	1500
Nb_3Sn	18.45	34	190	220,000
Nb-25%Zr	10.8			80,000
Nb-50%Ti	9.5			120,000

Practical importance of Types I and II

The practical significance of the separation into the two types of superconductivity now becomes clear. In Type I the superconductivity is 'quenched'—that is, vanishes—on exposure to relatively low magnetic fields, since the value of H_c is usually only a few hundred gauss. But Type II superconductors possess two critical fields, and although H_{c1} is also low, H_{c2} can be very high indeed.

Type II superconductors consequently fulfil one of the requirements of a material for use in a superconducting magnet, since superconductivity persists in the presence of the necessary high fields. A further requirement for magnet applications, however, is that the material shall also sustain a large transport current, which brings us to the effect of structural defects in a superconducting material on its critical current.

Role of defects in Type II

The influence of defects arises because of their ability to interact with the magnetic flux. Structural defects known to influence the low-temperature properties of superconductors include dislocations, precipitates of second phases, grain boundaries, martensitic transformations and voids.

At field strengths above H_{c1} magnetic flux penetrates the superconductor in the form of flux tubes or filaments. In defect-free material these filaments are able to move easily into the superconductor to take up their equilibrium configuration of a triangular array. Removing the field reverses the process, and the filaments move out.

It has been found, however, that defects in the material are able to 'pin' the flux filaments and prevent or restrict their movement. Consequently, flux entry is delayed and flux escape is partially prevented, which results in hysteretic magnetization curves, and the existence of flux gradients in the material at a given field.

Thermal activation helps some filaments past the pinning barriers at a given temperature and field, and there is a temperature-dependent 'flux-creep' process in which the creep rate of the flux filaments is governed by a relationship of the form

$$\exp\left(\frac{-Q}{RT}\right)$$

where Q is an activation energy. In defect-free material the creep rate is high and flux equilibrium is obtained; in defect-containing material the rate is low.

The presence of defects to pin the flux filaments is important because they increase the capacity of the superconductor to carry current without dissipating power. Defects can be introduced and controlled by standard metallurgical processes such as cold-working, heat-treatment, ageing or sintering. There is an optimum size and separation of the defects for maximum effectiveness in flux-pinning in given circumstances. Fig. 2.4 shows, for example, the effect of successive heat-treatment of cold-worked niobium (a Type II superconductor) on its magnetization curve at 4·2 K. The area of the hysteresis loop and the effect of pinning passes through a maximum value as the dislocation networks and interstitial precipitates are progressively altered by the heat-treatment process.

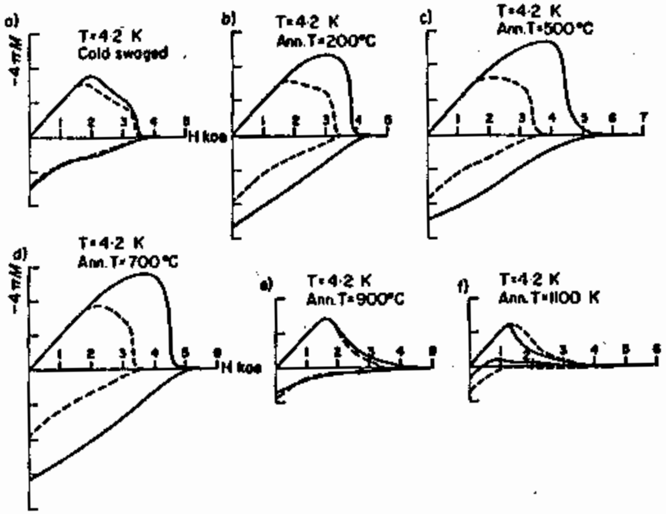

Figure 2.4 Effect of heat-treatment temperature (°C) on the magnetization curves of cold-worked niobium wires at 4·2 K

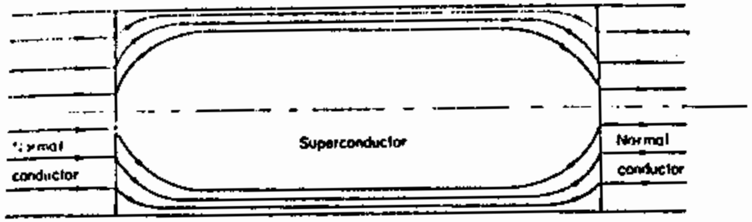

Figure 2.5 Current flow from a normal metal to a superconducter in a rectangular bar, in zero field.

Mechanism of current flow

It has been shown theoretically by London that when a transport current from an external source is passed through a Type I superconductor, the current is confined to a thin surface layer about 0·1 μm in depth, known as the 'penetration depth' (see Chapter 1). Fig. 2.5 shows diagrammatically the current path under these circumstances. If the superconductor is in the form of a wire of radius R, the maximum current I_c that can be passed before the superconductor is driven normal is given by 'Silsbee's Rule'

$$H_c = \frac{I_c}{5R} \qquad 2.3$$

In other words, this condition occurs when the surface field produced by the current in the wire equals the critical field. I_c is then the 'critical current'. An external field H applied transversely to the wire while it is carrying a current modifies this relation to

$$2H + \frac{I_c}{5R} = H_c \qquad 2.4$$

In a Type II superconducting wire containing defects, the mechanism of the current flow depends upon the strength of the external field H, and three regions of behaviour can be distinguished. First, for field strengths between 0 and H_{c1}: in this region the magnetic flux has not penetrated the material, and transport currents passed through the material are confined to the surface layer, as in Fig. 2.5. The maximum current is given by a relation similar to that for Type I

$$2H + \frac{I_c}{5R} = H_{c1} \qquad 2.5$$

with H_c replaced by H_{c1}.

Secondly, for field strengths between H_{c1} and H_{c2}: in this region the magnetic field penetrates, in the form of filaments, and the current flow is complicated. In the presence of a transverse magnetic field H and a transport current J, a Lorentz force F_L is exerted on the flux filaments equal to

$$F_L = J \times H \qquad 2.6$$

The Lorentz force acts in a direction perpendicular to both J and H. The filaments accordingly move through the material with a velocity v under the driving action of the Lorentz force, and their motion is resisted by the 'pinning force' F_p provided by the presence of the defects. This process naturally requires power in order to continue, a power equal to

$$p = n.F_p.v \qquad 2.7$$

where n is the number of filaments. The power required to move the filaments against the pinning action of the defects corresponds to an apparent electrical resistance on the part of the superconductor, with a consequent appearance of a voltage. This is the voltage measured in 'critical current' experiments on superconductors, where the 'critical-current' J_c is defined as the maximum current passed before a measurable voltage first appears. To some extent, therefore, critical current values are arbitrary since they depend upon the sensitivity available for the level of voltage detection. In principle, voltage will appear for *all* values of current, although in practice little significance is attached in these measurements to voltages below about 0·1 μV. The critical currents drop to very small values as the magnetic field approaches H_{c2}, the typical curves of J_c versus H for some well-known commercial superconductors are shown in Fig. 2.6.

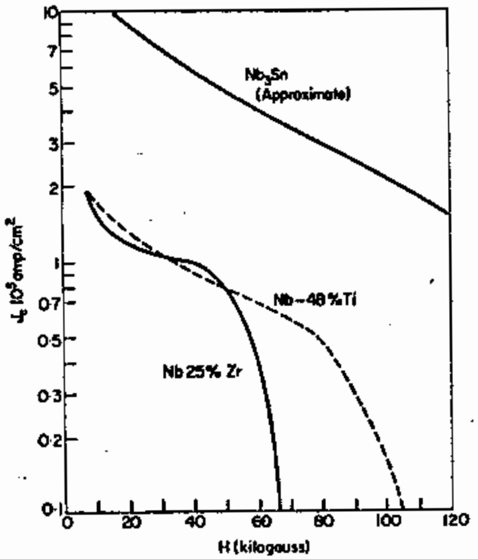

Figure 2.6 Typical curves showing how the current-carrying capacity of well-known superconductors varies with field strength.

The third region we can distinguish covers field strengths above H_{c2}. In this region flux penetration into the material is complete and superconductivity has virtually disappeared. Both theory and experiment have shown, however, that in regions where the external field lies parallel to the surface of the material, it is possible for surface superconductivity to persist up to a field equal to 1·69 H_{c2}. The current carried by these regions is very small, and appears to have little practical significance.

Development of magnet materials

It should be remembered that the technological development of Type II superconductors in the period following 1961 was aimed at producing superconducting magnets, and hence the passing of *direct* current through the material. The mechanism of the current flow described earlier is the mechanism envisaged for direct current. Later, I shall mention the materials problems associated with *alternating* current effects.

Soon after the discovery of superconductivity by Kamerlingh Onnes the possibility was realized of generating magnetic fields as large as 100 kG by the manufacture of solenoid magnets. With the further discovery that superconductivity in the then-known materials was destroyed by fields of a few hundred gauss, the opinion developed that superconducting magnets capable of even a few kilo-gauss were not feasible. The requirement of a useful high-field superconductor is that it shall sustain a reasonably high current density (10^4–10^5 A/cm^2) in a field of 50 kG or more. No materials were known capable of meeting this specification. The upper limiting field of a magnet material on the GLAG model is the field H_{c2}, and this in turn depends upon the value of κ.

The discovery that the compound niobium–tin would remain superconducting in very high fields (220 kG according to the most recent measurements) while carrying currents of more than 10^5 A/cm^2 at lower fields revived interest in the technology. Further work has shown that the alloys niobium–zirconium and niobium–titanium are also able to operate as useful materials, up to 80 and 120 kG, respectively (see Table 2.1). These three materials have so far received the greatest commercial development.

In order to wind a superconducting solenoid the superconductor needs to be in the form of long lengths of wire, strip or ribbon. The methods of manufacture evolved for commercial materials depend on the fact that the niobium–zirconium and niobium–titanium alloys are ductile, whilst the niobium–tin compound is extremely brittle.

Niobium–zirconium alloys. These alloys were the first high-field materials to be produced as long lengths of wire, and the alloy containing 25 per cent zirconium has received the most attention. The alloys have the body-centred-cubic (b.c.c.) crystal structure above 800°C, and this structure can be retained by moderately rapid rates of cooling. The b.c.c. structure is favourable for the use of conventional metallurgical fabrication processes involving heavy deformation of the material. The workability of the alloys—in common with other b.c.c. refractory metals—is markedly affected by the presence of interstitial impurities such as oxygen, nitrogen and carbon. It is necessary to exclude these elements at all stages of preparation.

The starting materials are iodide zirconium and very pure (electron-beam melted) niobium. These are melted together in an argon-arc or electron-beam furnace. The ingots so formed are encased in stainless steel or molybdenum jackets, reduced to bar by hot extrusion and hot swaging, and subsequently cold swaged and drawn to wire or rolled to strip. A short heat-treatment in the range 500–700°C improves the current-carrying-capacity of the wire, because of the rearranged dislocation networks, and also through the appearance of a small quantity of fine precipitate at grain boundaries.

Niobium–titanium alloys. Within the past two or three years niobium–zirconium alloys have been displaced in commercial usage by niobium–titanium alloys, containing 45–50 per cent titanium, which are more ductile, so that fabrication is easier and the superconductor is cheaper. Niobium–titanium alloys can also operate at higher fields. In principle, the processing routes are similar to those for niobium–zirconium, although the final heat-treatment is usually in the range 350–450°C. In addition, these alloys are usually marketed clad with copper, for reasons to be described later. Niobium–titanium alloys are much more compatible with copper, in terms of workability, than the niobium–zirconium alloys.

Niobium–tin compound. The principal difficulty with niobium–tin is its inherent brittleness, bearing in mind the fact that the superconductor must be capable of being wound into a solenoid without subsequent deterioration in its properties (such as would occur if the material were to fracture). The way this is achieved in practice is to

ensure that the material is in the form of a sufficiently thin deposit, a few micrometers deep, laid on to a supporting metallic substrate, so that the composite structure can be bent without damage to the superconductor. Two methods have been developed commercially: the vapour-deposition method, and the diffusion method.

The principle of the vapour-deposition technique, developed by the Radio Corporation of America is the simultaneous hydrogen reduction of a mixture of a gaseous niobium and tin chlorides on to a hot stainless-steel strip. If the proportions of the chlorides are correct, the deposit will consist of the compound Nb_3Sn. Niobium and tin are chlorinated separately in a stream of gas at a temperature between 800 and 900°C. The gaseous chlorides are mixed together, hydrogen is injected into the gas stream, and the gases fed into a reaction chamber held at 700°C. The reaction takes place on the surface of the strip, which is heated electrically to 1000°C and passed continuously through the reaction chamber. The choice of the strip substrate material is critical; it must form a good bond with the compound as well as matching it in terms of thermal expansion.

The diffusion process has been developed by the U.S. General Electric Company. Here, an initial layer of tin of the required thickness is formed on a niobium strip by dipping, evaporation, or electroplating, and the laminate treated at 1000°C to form Nb_3Sn by reaction between the tin and the niobium. By adjusting the processing parameters a niobium–tin layer of the required thickness can be prepared. Such a tape does not have the mechanical strength of the vapour-deposited tape, whose substrate is stainless steel. However, the problem of mechanical strength can be overcome, as we shall see later. The diffusion process can also be adapted to form multi-strand wire by drawing down a number of tin-coated niobium wires together in a niobium or copper jacket, and then heat-treating the assembly.

In using these three materials for the construction of magnets, two problems have emerged: stability in operation, and mechanical strength.

Stability of magnet material

When a superconducting wire or strip is wound into a solenoid and the current progressively increased, the field in the centre of the solenoid also increases. This process necessarily also entails a progressive penetration of magnetic flux into the material of the winding itself. As has already been shown, the motion of flux through a Type II superconductor requires a power $nF_p v$, and this power is dissipated in the form of heat. The material, however, is always immersed in liquid helium, and so under good conditions increasing the current merely causes a slight increase in the boil-off rate of the helium, which becomes very small once the current has reached a steady value.

Under the conditions existing within a coil, good thermal environments do not always occur. Consequently the local temperature in part of the superconductor may rise above that of the helium cryostat. A rise in temperature promotes the motion of flux through the material, with the dissipation of still more heat, and through a runaway process the superconductor may eventually revert to its normal resistive state. At this point, if the current supply is not quickly switched off, the material may melt locally.

This problem was encountered in the first few magnets to be constructed. The wire was able to pass much less current as a coil than in the form of a short length. The solution lay in cladding the superconductor with high-purity copper to make a composite. The high thermal conductivity of the copper smoothed out local hot spots, and the high electrical conductivity meant that in emergencies the copper could also act as a protective current shunt without dissipating too much power.

All three high-field superconducting materials are now commercially available clad with copper. The copper is added to the niobium–zirconium or niobium–titanium alloys either by cabling copper wires with superconducting wires and bonding the assembly together with indium or solder; or by enveloping the superconductor with copper early in the fabrication route and then reducing the clad assembly to bar, wire or strip. Complex configurations of superconducting wires in a copper matrix can now be produced in this way, depending upon the special requirement of the user. The copper can be added to niobium–tin strip by simply soldering copper strips on each side to make a sandwich.

Strength of magnet material

In addition to the thermal, electrical and magnetic behaviour of the superconductor, consideration must also be given to its mechanical strength. In a solenoid operating at high fields there is a considerable bursting force on the windings, giving rise to hoop stresses. There is also an axial compressive force on the solenoid as a whole. These stresses are discussed in more detail in Chapters 3 and 4. In very large magnets, such as those for bubble chambers, these forces may exceed the strength of the composite, and it becomes necessary to include in the composite strengthening members such as stainless steel. Stainless steel wires can be included in the cables, or stainless steel strip incorporated to make a multi-layer sandwich (Fig. 2.7).

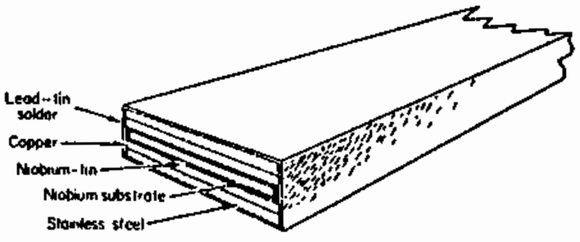

Figure 2.7 Sketch of the cross-section of a composite superconductor.

Behaviour of a.c. in Type II superconductors

Although under steady d.c. conditions Type II superconductors can be operated so that the very small level of power dissipation (since $nF_p v$ never vanishes entirely) can be neglected, there will be losses if the current is continually changing. Let us look at the origin of these losses in another way. The a.c. creates an alternating field at the surface of the superconductor, so that with high peak currents the material is constantly being driven around its cycle of magnetization. We know that the magnetization curves of the defect-containing Type II superconductors exhibit marked hysteresis (Fig. 2.3), so the energy losses that occur under a.c. conditions are hysteresis losses. It is clear that no hysteresis losses need be expected if the peak surface field produced by the current remains less than H_{c1}, since no flux should penetrate the superconductor.

In practice, losses do occur in this region, owing to small pockets of flux trapped at surface defects or at surface roughness. Very smooth surfaces such as those produced by electropolishing are required to minimize these effects. If the field produced by the current exceeds H_{c1}, hysteresis losses appear which at low frequencies (0–5000 Hz) increase linearly with frequency. Since the depth of penetration of the field is usually small, it is customary to describe the losses as surface losses. The loss per square centimetre of surface is found to be proportional to $H_m^3 f/J_c$ or $I_m^3 f/J_c$, where f is the frequency, H_m the peak alternating field, I_m the peak alternating current and J_c the d.c. critical current density.

Generally speaking, the high-field Type II materials used in d.c. applications, such as magnets, are unlikely to prove acceptable for a.c. applications, owing to the high losses, the reason being their low values of H_{c1}. To ensure that losses are low, the penetration of flux into the material must be avoided if possible. In other words, I_m or H_m must be less than H_{c1} if a Type II material is used, or less than H_c if a Type I material is used.

Fig. 2.2 shows that in Type II materials, which are important for magnets, high values of H_{c2} are unfortunately associated with low values of H_{c1}. Niobium–titanium, niobium–zirconium and niobium–tin all have H_{c1} values of only 100–300 gauss. One may compare these values with those of the elemental superconductors: lead (Type I) has an H_c of 530 gauss at 4·2 K; niobium (Type II) has an H_{c1} equal to 1200 gauss at 4·2 K. The alloys are therefore likely to be more prone to loss above 100–300 gauss than the elements since the alloys will be operating in the 'mixed state' region.

Enhancement of superconductivity

The three most important properties of a superconductor are the critical temperature T_c, the critical current J_c, and the critical field H_c, or H_{c1} and H_{c2}. It is obvious that there is a continuing interest, both scientific and technological, in increasing these values beyond those known at the present time. The three properties are not independent of one another, and a qualitative relation between them is shown in Fig. 2.8. Between the origin and the surface is the region of practical interest, and one hopes to be able to push this surface outwards. Let us take them in turn.

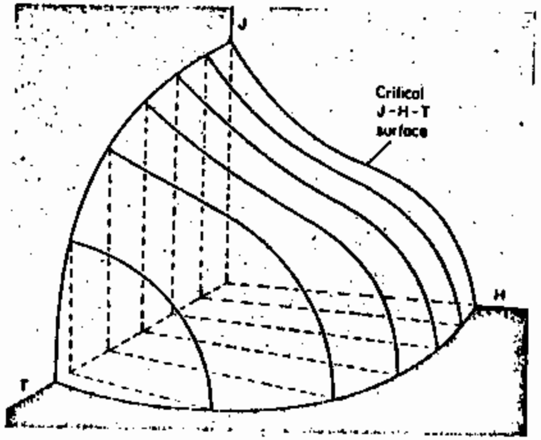

Figure 2.8 Superconducting region bounded by the critical J-H-T surface. (The superconduction region lies below this surface, the normal region above it.)

The critical current. Considerable progress has been made in understanding the role of defects in pinning flux lines and in raising J_c in both niobium and the two ductile alloys. The effect of dislocations and sub-grain-boundaries on the low-temperature properties has been ascertained by a combination of superconducting measurements and

transmission electron microscopy. The precise effect of interstitials and the interstitial precipitates assumed to be created by heat-treatment is not yet clear, however, since the improvement of J_c is related to effects beyond the resolution attainable by existing techniques of microscopy.

Great advances have been made recently in observing the actual distribution of flux filaments in a material by using a method of depositing fine ferromagnetic powder on to the superconductor while it is in a magnetic field. The particles are attracted to the areas containing magnetic flux in the superconductor, and deposited on to them. Electron microscopy of the deposit has revealed the theoretically-expected triangular lattice of flux lines (Fig. 1.7). It has also revealed defects in the flux lattice, such as grain boundaries and vacant sites; defects well-known in the structure of solids.

Systematic application of this technique to superconducting materials should improve the understanding of the mechanism by which structural defects in a material establish flux gradients and high values of J_c. Consequently, further improvements in values can be expected. It is by no means clear, for example, which factors give the brittle niobium–tin compound its high current carrying capacity, since dislocations cannot be introduced into this material by cold-work. One suggestion is that a low-temperature martensitic transformation is responsible for the properties.

The critical field. The value of H_{c2} in Type II superconductors is important in magnet application, and niobium tin has a value of about 220 kG, compared with 80–120 for the ductile alloys. As we know, increasing the resistivity of a Type II alloy superconductor increases its κ value (see Equation 2.2, p. 21) and an increase in κ increases H_{c2} (Fig. 2.2). In principle, therefore, one would expect alloying to offer the opportunity of obtaining higher critical fields. Unfortunately, many elements when dissolved in niobium-tin, for example, have an adverse effect on the critical temperature. Nevertheless, there is scope in this area for more investigation.

The critical temperature. Over a thousand metals and compounds are known to exhibit superconductivity. Empirical rules governing the relation between critical temperature and the average number of valence electrons per atom have been put forward by Matthias. Considerable attention has also been paid to the relation between critical temperature and the various types of crystal structure of superconducting compounds.

The highest values of critical temperature appear to be confined to the 'beta tungsten' and 'alpha manganese' lattices, and the relation between critical temperature and the average number of

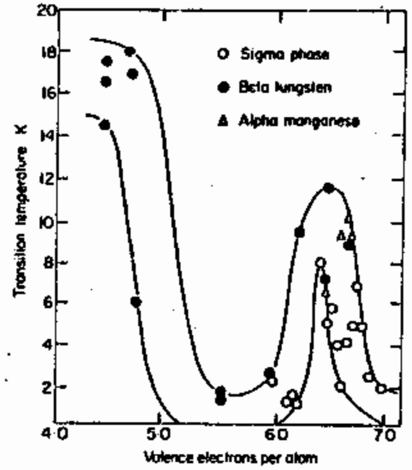

Figure 2.9 Superconducting transition temperature as a function of the average number of valence electrons per atom.

valence electrons is shown in Fig. 2.9 for three different crystal structures. Some values of T_c are shown in Table 2.2.

In endeavouring to raise values of critical temperature above those known at present it has been the practice to use the beta-tungsten crystal structure as a platform, and to substitute a different atom for either of the original constituents, in the hope that T_c will increase. In general the effect has been to reduce T_c. Recently, however, a **critical temperature of 20·7 K has** been achieved in an alloy of **Nb_3 (Al, Ge),** in which germanium is substituted for aluminium in the **Nb_3Al** structure. Efforts in this direction are still continuing.

TABLE 2.2 *Some values of critical temperature*

Structure	*Compound*	T_c, K
Beta-tungsten	Nb_3Sn	18·45
,, ,,	V_3Ga	16·8
,, ,,	Nb_3Ga	14·5
,, ,,	Nb_3Al	17·1
,, ,,	V_3Si	17·0
Sigma	Nb_3Pt_3	4·2
,,	Nb_3Ir_2	9·8
,,	Cr_2Ru	2·02
Alpha-manganese	Re_3Mo	9·8
,, ,,	Re_3W	9·0
,, ,,	Re_3Ta	6·78

A fourth structure favourable for superconductivity is the simple cubic sodium chloride type structure of the transition metal carbides or nitrides, such as niobium carbide (NbC). Mixtures of these nitrides and carbides have approached critical temperatures of 18 K.

The phenomenon of superconductivity has been observed in a range of different compounds the constituents of which are both metallic (Nb_3Sn), or mixed metallic and non-metallic (NbC), or semiconducting (GeTe; $SrTiO_3$; Na_xWO_3), and also in graphitic compounds of the type C_8K_8. The number and variety of such compounds is steadily increasing, although the highest critical temperatures by far are still those of the beta-tungsten structure mentioned above.

The theory of superconductivity established in 1957 by Bardeen, Cooper and Schrieffer (the BCS Theory: Chapter 1) is based on an interaction between the valence electrons and the vibrations of the crystal lattice (or the phonons). Other mechanisms have, however, been suggested from time to time for the creation of the superconducting state. These suggestions include the possibility in certain transition metals of electron-electron rather than electron-phonon interactions; the possibility of superconductivity appearing in rare-earth metals only when they are placed in very high magnetic fields; and the possibility that certain organic molecules might exhibit superconductivity with very high critical temperatures.

This last suggestion, made by Little, has aroused some controversy. The possibility that certain molecules might exhibit superconductivity was made by London in 1950. Little re-opened this question in 1964. He considered that in a long-chain molecule consisting of alternately doubly and singly bound carbon atoms, such as an organic polymer, with a complex resonating aromatic-dye type of side chain attached to every alternate carbon atom, it might be possible to induce one-dimensional superconductivity in the long-chain 'spine' molecule.

If the constituents of the side chain were chosen correctly, oscillations of charge along the side chain would fulfil the function of the phonons in the BCS theory, and induce electron pairing and superconductivity in the spine, with a high—perhaps even as high as room temperature–value of T_c. The critical temperature (T_c) in the BCS model is given by

$$kT_c = 1{\cdot}14\hbar\omega_{ph}\exp(-1/N(0)V) \qquad 2.8$$

where $\hbar\omega_{ph}$ is related to the lattice-vibrations, $N(0)$ to the distribution of valence-electron energy, and V to the electron-phonon interaction.

All these values, and the balance between them, however, are highly dependent upon the nature of the model system one chooses. Little's suggestion has since been criticized on a number of different grounds, one of which is that one-dimensional superconductivity (along the spine) is not theoretically possible. At the present time the possibility of materials of this kind exhibiting superconductivity seems unlikely.

Other methods of raising critical temperatures are being investigated at the moment, a recent technique being the production of 'granular' superconductors. It has been known for many years that some superconductors, when composed of small grains (20–200 Å in diameter), have critical temperatures appreciably higher than their ordinary values. Films have been prepared by evaporation on to substrates held at 4·2 K. However, upon warming to room temperature grain growth occurred and the critical temperature returned to the normal values.

More recently films of high T_c of the same metals have been prepared by evaporation in an oxygen atmosphere. The observed increases in the critical temperature were of the same magnitude as those obtained by the low-temperature evaporation technique, but they did not change upon storing at room temperature. These films also exhibited high critical fields and high normal resistivities. It is believed that these properties arose from the precipitation of oxygen at the grain boundaries, which prevented grain growth and formed 'tunnelling' barriers between grains. Aluminium ($T_c = 1{\cdot}2$ K) has been prepared in this way with a critical temperature of 3·7 K.

Prospective superconductors

To summarize, the prospect for obtaining superconductors with critical temperatures much in excess of the highest value known (20·7 K) seems remote at present, unless new mechanisms for creating the superconducting state are discovered. From the point of view of the development of materials, the following five areas are likely to engage the most attention for the next year or two.

First, a reduction in the cost of superconductors, by improvements in metallurgical processing or by raising J_c, or both. Second, exploration of the temperature-dependence of J_c, so that operation above 4·2 K may be assessed. Third, exploration of systems in which $\partial J_c/\partial T$ is positive over some range of temperature, for thermal stability under d.c. or a.c. conditions. Fourth, development of metallurgical processes for incorporating fine filaments or films within insulating or high-resistance material, for a.c. applications (see also Chapter 3). And finally, the search for higher values of critical temperature.