Solid State Science and Technology, Vol. 11, No.1 (2003) 73-82

HIGH TEMPERATURE SUPERCONDUCTOR MATERIALS AND APPLICATIONS

Roslan Abd-Shukor
School of Applied Physics
Universiti Kebangsaan Malaysia
43600 Bangi Selangor Malaysia
ras@pkrisc.cc.ukm.my

ABSTRACT

Research on materials continues to play a pivotal role towards the advancement of technology. One of the promising materials for advanced electrical and electronic applications is the copper-oxide-based high temperature superconductor (HTSC). Today, the focus is once again on superconductivity following a number of breakthroughs and discoveries in this field in recent years. In this paper, a number of newly discovered superconducting materials would be discussed. Applications of superconductors in various sectors such as the communications, power and electronic are highlighted. A superconductor-magnetic nanorod hybrid system which can potentially increase the ability of superconductors to carry current by many folds is also discussed.

INTRODUCTION

The field of superconductivity undergoes a major revolution in 1986 following the discovery of high temperature superconductivity (HTSC) in copper-oxide-based ceramics [1-2]. A number of copper oxides based ceramics were found to superconduct and they include the La-Ba-Cu-O, Y-Ba-Cu-O, Bi-Sr-Ca-Cu-O, Tl-Ba-Ca-Cu-O and Hg-Ba-Ca-Cu-O systems. Hitherto, the Hg-Ba-Ca-Cu-O has highest superconducting temperature of 134 K.

Superconductor can conduct electricity without any resistance (Figure 1) below a critical temperature T_c. It also acts as a perfect diamagnet. These two properties can be used in many applications. In general, the applications of superconductors can be divided into two categories, large-scale and small-scale. Large-scale applications normally employ materials in bulk form. Thin film applications such as in microwave devices and SQUIDs are examples of small-scale applications.

The discovery of HTSC materials which superconduct above the boiling point of liquid nitrogen has prompted intensive research worldwide. The lower cooling cost provides the opportunity for a wider scope of applications. The estimated global market for superconductor-based products by year 2020 is about US$150 billion.

A number of new superconducting materials have been discovered in recent years. In early 2001, Japanese scientists reported superconductivity in magnesium diboride at 39 K which almost doubles the transition temperature of any other metallic superconductor [3]. Table 1 shows the classes of superconducting including some novel superconducting materials discovered recently.

In this paper we will discuss the various applications of superconductors. The electrical transport properties of high temperature superconductor tapes will be reported along with the possibility of a frozen flux superconductor in a superconductor-nanomagnet hybrid system.

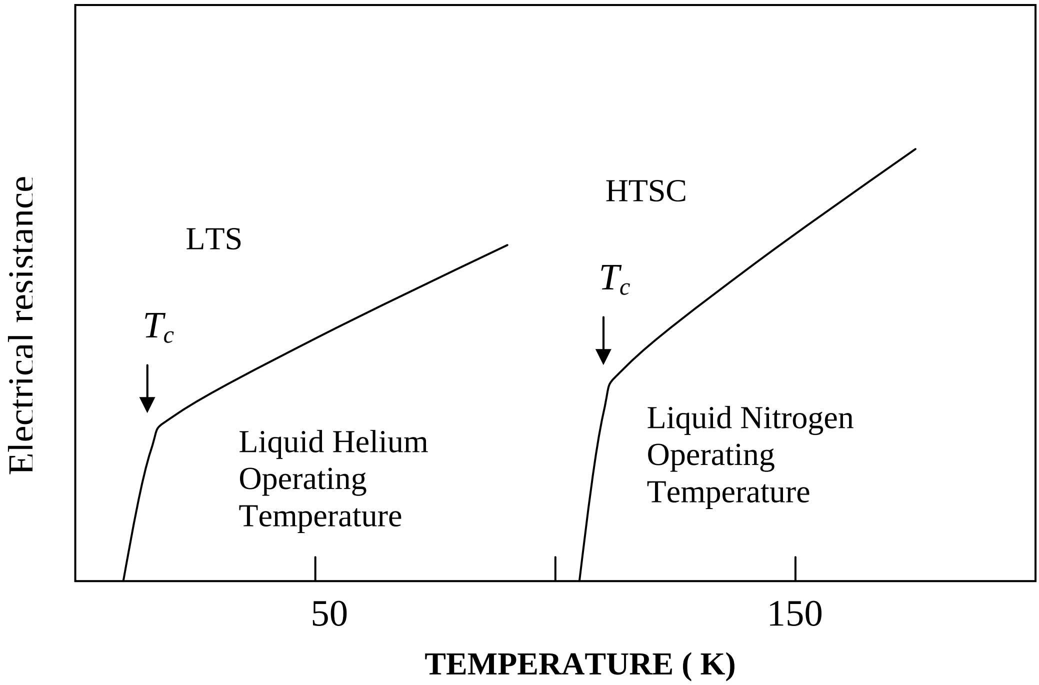


Figure 1. Electrical resistance versus temperature of superconductors. LTS is low temperature superconductor. HTSC is high temperature superconductor.

Table 1. Conventional and novel superconducting materials.

Materials	Example	T_c (K)
Metal and alloys	Al, Pb, Nb_3Sn, NbTi	< 23
Organic Salts	BEDT-TTF$]_2$X	< 12
Heavy Fermions	$CeCu_2Si_2$	< 1
Borocarbide and boronitride	$LuNi_2B_2C$	< 23
Oxides base (Bi, Ti, Sr)	$Ba_{0.63}K_{0.37}BiO_3$, $SrTiO_{3-\delta}$	< 30
Copper oxide based	YBCO, BSCCO	< 134
Recently Discovered Novel Superconductors		
C_{60} based		< 42
DNA		< 1
Acenes Crystal		< 4
MgB_2		39

APPLICATIONS

The main reason a particular technology is employed over another is due to its practicality and superior performance. The two special properties of superconductor namely zero resistance and perfect diamagnetism can be capitalized in many applications. Conventional superconductors have already found their way in a number of commercial applications even though complex cryogenic system is required for operation, simply because they provide the best performance. Some of the advantages of using superconductors include low-noise, high sensitivity detection of low frequency signals and generation of extremely high magnetic field. Superconductor technology should be substantially superior in performance than competing technologies if it were to overcome the principle barrier i.e. refrigeration.

Some of the problems that complicate applications of HTSC include (i) low transport critical current density, (ii) poor mechanical strength and (iii) metastability. Research efforts are being carried out worldwide to overcome these problems.

Transport critical current density is the maximum current that can be carried by a superconductor for a given cross-sectional area before the material becomes non-superconducting. Current density in HTSC can be enhanced by proper processing procedure. Superior mechanical strength is important in ensuring the reliability of these materials in various environments. Novel preparation techniques can be employed to improve the mechanical properties.

SUPERCONDUCTOR IN COMMUNICATION

For a filter designer, superconductors provide the closest approximation to a perfect filter. Namely, one that allows 100% of the desired signals to pass through and rejects 100% of the unwanted signals (Figure 2). For this reason, superconducting filters are ideally suited for rejecting out-of-band signals including those that are very close in frequency to the desired band.

Wireless service providers worldwide are scrambling to add more capacity to their networks. It is one thing for the providers to sell more phones and service contracts to consumers with their marketing campaigns, but it's another thing actually to accommodate the surging number of calls being made. Each wireless base station which, broadly speaking, are poles with switches at the bottom and antennae at the top can only handle a certain number of calls at a time. When a limit is exceeded, calls are dropped, static rises or calls can't get through.

Superconductor filters with super-cooled materials offer virtually no electrical resistance and solve many problems. Distortion and noise are reduced dramatically, boosting the capacity of some base stations by as much as 50%. This means far fewer "dead spots" in networks, and more customers can be kept online. Because signals are clearer, it is less likely that bits will be dropped in data communications. Furthermore, well-filtered transmissions require less power to transmit thus prolonging battery life for handset users and cutting costs for transmitters. The same property is also useful in satellite communication systems

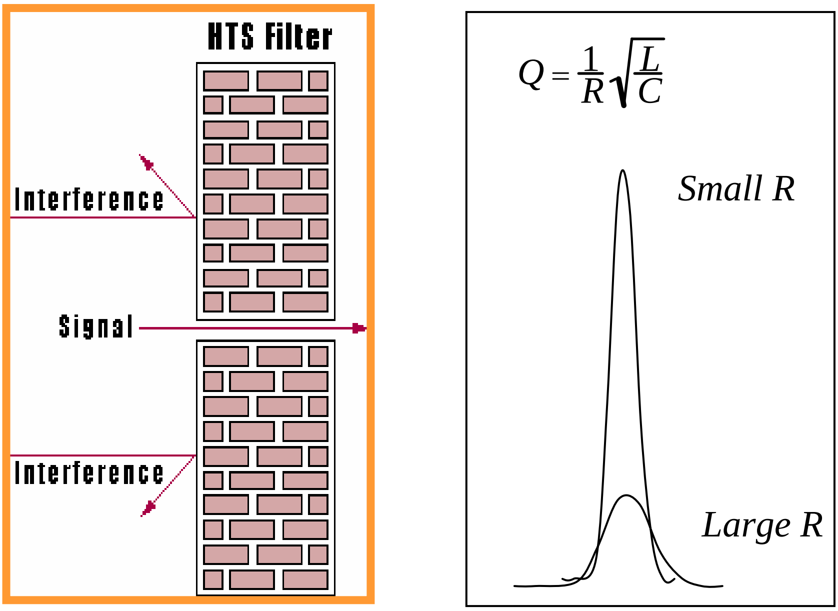


Figure 2. Brick wall effect and quality factor Q in filters. Negligible resistance R gives rise to high Q in a HTSC filter. L is the inductance and C is the capacitance.

POWER APPLICATIONS OF SUPERCONDUCTOR

Materials for power applications usually need to have substantially high transport critical current density (J_C) and be able to withstand stress generated by high magnetic field. In addition, these materials should to be easily drawn into wires and tapes. Conventional superconductor such as NbTi which can be easily drawn into wires and tapes is the most widely used superconductor alloy today.

Supermagnets employing liquid helium have been successfully used in engineering, medical equipment, mining and transport system. These systems integrate several other technologies with superconductivity as the main technology.

SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

Electrical energy is the most important form of energy today. The increasing demand in electrical energy requires the generation of even more supplies. The demand of energy is not constant throughout the day. It is high during the day but decreases by 50 % during the night. The electrical energy generated during the night can be stored and utilized during the day. This will allow the constant generation of energy throughout the day which can reduce the maintenance cost of generators. One of the methods to store energy is by using superconductor as magnetic energy storage.

The schematic circuit of superconducting magnetic energy storage (SMES) system is shown in Figure 3. It consists of a superconducting coil placed in a coolant bath. The total
energy E stored depends on the current, I and the inductance, L in the circuit and can be written as $E = \frac{1}{2} L I^2$.

SMES system does not present major harmful environmental effect. This system does not require the burning of carbon and does not require major environmental alterations such as building of dams. The high magnetic field generated by this system may however, pose a danger but proper safety precautions such as warning signs can prevent any potential hazards. This system can be used when large amount of energy is required within a short period of time such as in laser applications which is important for defense purposes. SMES system has 90 - 95 % efficiency and the energy loss is mostly due to the conversion from dc to ac and also the energy required for cooling.

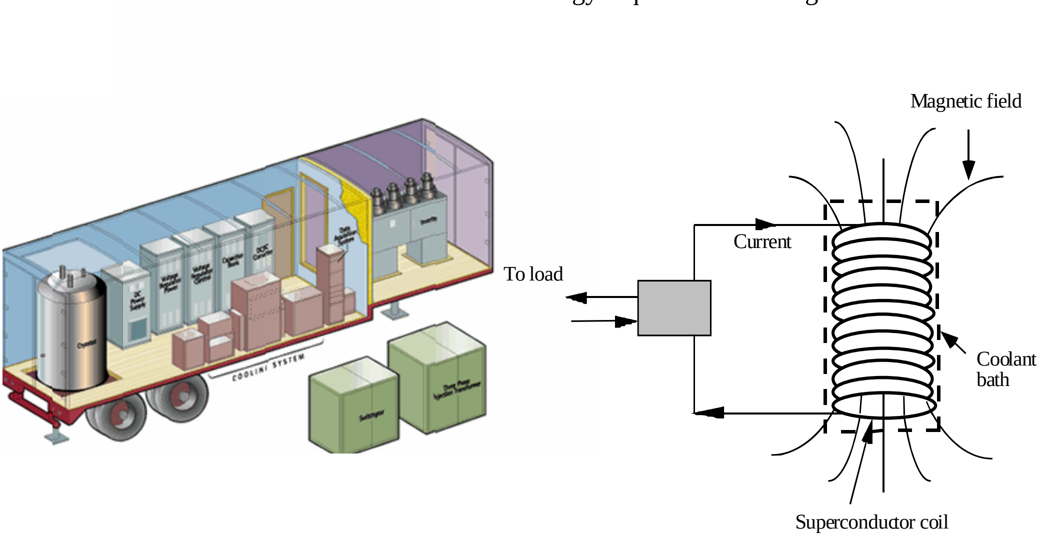


Figure 3. Mobile unit of SMES [7] and the schematic.

FAULT CURRENT LIMITERS (FCL)

Any electrical device is at risk of a short-circuit current and some kind of protection is usually employed. A simple fuse box or modern circuit breakers are examples of this protection system. Beyond our homes, the electrical utility has to worry about problems such as lightning and other unexpected circumstances during transmission and distribution [4].

A simple illustration of HTSC based FCL is shown in Figure 4(a). Under operating condition, the superconducting element is in its superconducting state and the current passes through without losses. In the event of a fault current where the critical current is exceeded, the superconductor will revert to the non-superconducting state and becomes a series resistance that limits the current. However, all of the energy will be dissipated through the superconductor. This arrangement will increase the reset time.

Figure 4(b) shows a configuration that can reduce the dissipation of thermal energy through the superconductor. In this case a shunt impedance is used as the limiting element.

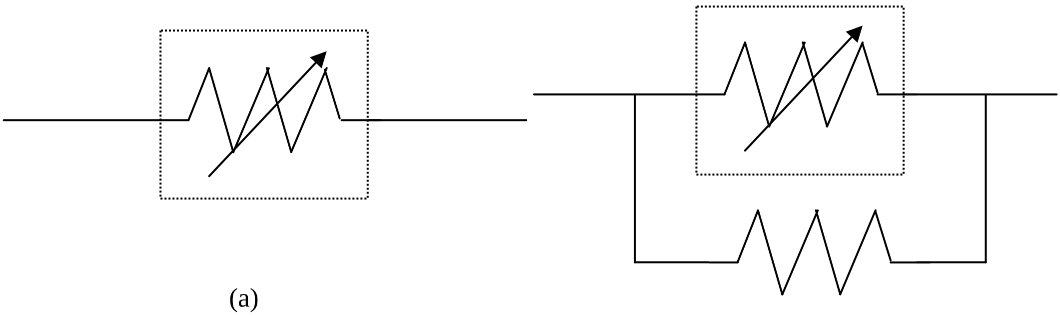


Figure 4. (a) A simple schematic of FLC and (b) FLC with shunt impedance to eliminate thermal dissipation through the superconductor. Portion in dashed line is held at cryogenic temperature.

MOTORS AND GENERATORS

The size, loss and weight of HTSC motors are expected to be half of the conventional motors. Rotor losses can be eliminated and armature losses can be reduced. With electric motors accounts for more than one half of energy demand, replacing conventional motor with HTSC motors will allow a large amount of energy saving. Various laboratories have made much progress in the development of HTSC motors.

In transformers, small improvement in efficiency can lead to substantial energy savings. Although low temperature superconductors are currently being used in generators, the availability of HTSC conductors will be much desired especially in the 300 MVA ratings [5].

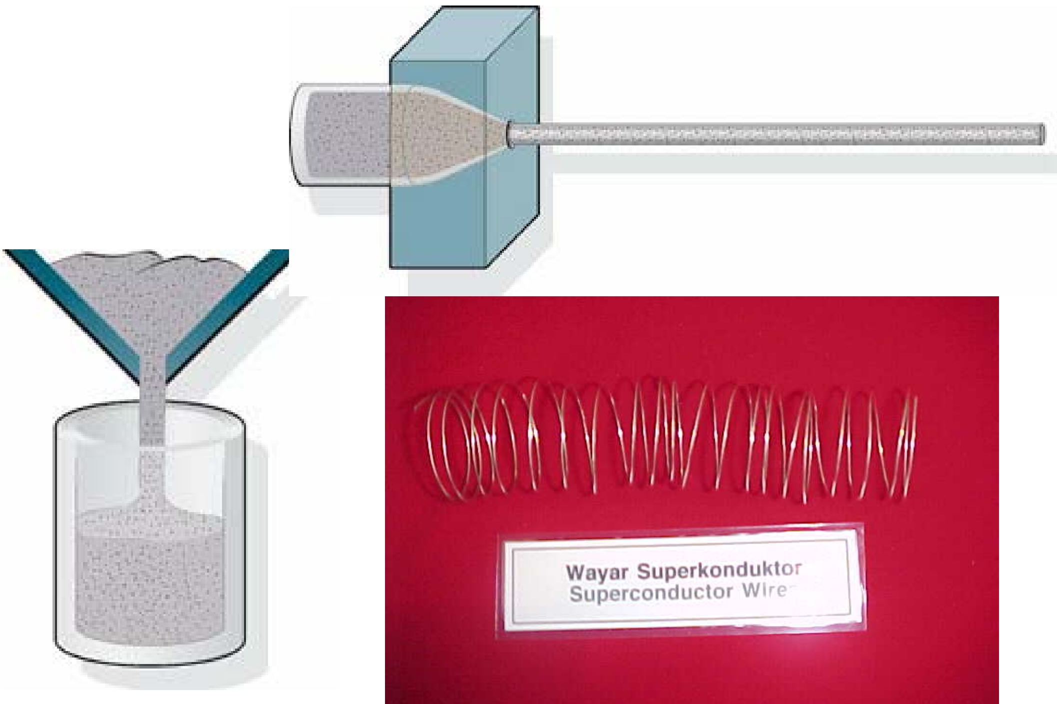
HTSC WIRES AND TAPES

The fabrication of ceramics HTSC materials into cables and wires has its share of problems. The silver sheathed bismuth-based superconductor tape ($J_c \approx$ 70,000 amp/cm^2) has been commercialized but its properties in magnetic field need to be improved.

Several methods of fabricating HTSC wires and tapes have been developed and one of them is the powder-in-tube method (Figure 5 (a) and (b)). Precursor powders are prepared by solid state reaction process consisting of superconductor powder such as Y-Ba-Cu-O, or metal oxides and pure metal which can react to form superconductor. These powders are then filled into metal tubes such as silver which is inert to the superconductor material and allows oxygen to pass through for oxidation. The tubes are then formed into wires by extrusion process and further formed into tapes by rolling process. The wires and tapes are then annealed at 800 ^{o}C - 900 ^{o}C in flowing oxygen. They can be bundled up into silver tubes and pulled again to form multifilament cables. Figure 5(c) shows a high temperature superconductor wire.

Frozen flux superconductors with magnetic nanorod insertion as shown in Figure 6 has been proposed [6]. If the size of the nanorod is much less than the coherence length, the vortex can be pinned with pinning energy $\varepsilon_M \sim \varepsilon_o \ln\frac{\lambda}{R}$ where R is the radius of the nanorod. In order to investigate this possibility we have inserted needle-like γ-Fe_2O_3 nanorod into Bi-2223 superconductor tapes with formula $Bi_2Sr_2Ca_3Cu_3O_{10}$–(γ-Fe_2O_3)$_x$. We found that the transport critical current density was enhanced for a small amount (x = 0.01) of the magnetic nanorod.

(b)



(a) (c)

Figure 5. Superconductor wires and tapes can be prepared by (a) filling superconducting powders into metal tubes such as silver followed by (b) extrusion into wires and into tapes by rolling. The final stage involves annealing at high temperature for oxidation. (c) HTSC superconductor wires. (Figure 1(a) and (b) from American Superconductor Corp. [7] and figure (c) from UKM).

The transport current of the tapes produced by the powder-in-tube method drop sharply in magnetic field (see Figure 7). Hence, other methods of producing HTSC tapes are also being developed. The next generation superconducting tapes are being studied in many laboratories. It basically consists of HTSC thin film on metal substrates. The selection of metal substrates and the superconductor materials is very crucial. Although the critical current density of the second-generation tapes is very high (10^6 amp/cm^2), they are very short in length. Nevertheless, second generation HTSC conductors in hundreds of meter length are expected to appear in a few years.

We have also investigated the transport current density in Ag-sheathed Tl-1212 and B-2223 tapes. The transport critical current density of Bi-2223/Ag and Tl-1212/Ag HTSC tapes subjected to various different thermo-mechanical treatments in low magnetic fields were compared. All the tapes display weak links dominant characteristic, which is more severe in the Tl-1212/Ag tapes. The Bi-2223/Ag tapes show larger anisotropic transport behaviour compared to Tl-1212/Ag tapes in applied field (Figure 8) [9]. This can be associated with the microstructural difference between these two types of tapes as revealed from SEM micrographs. Magnetic field dependence of J_c (H > 0.06 T) which shows a plateau-like behaviour was observed in Tl-1212/Ag tapes. This clearly indicates the stronger flux pinning properties in Tl-1212/Ag tapes. The strong interlayer coupling that results in much reduced of structural anisotropy may be responsible for the plateau in the Tl-1212/Ag tapes.

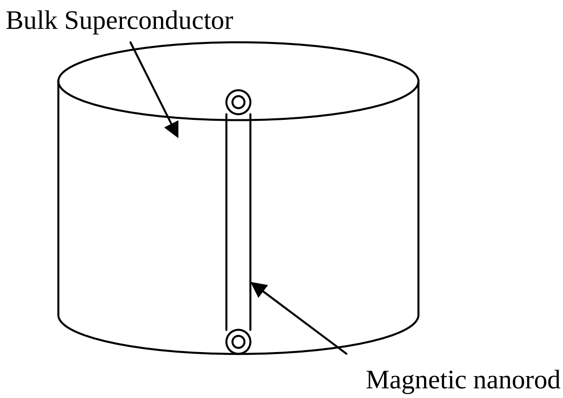


Figure 6. Vortex bound with magnetic nanorod

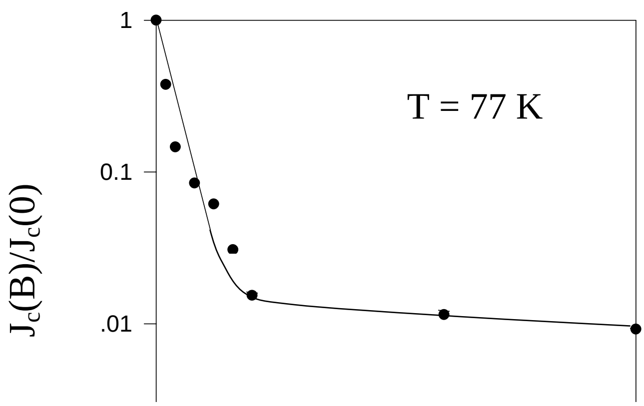


Figure 7. Sudden drop of the transport critical current density of a typical HTSC tape in magnetic field showing weak interconnectivity between superconducting grains [8].

CONCLUSIONS

The developments in HTSC research for the past 16 years have been impressive, albeit slow commercialization. The use of liquid nitrogen instead of the more expensive liquid helium has renewed the possibility of superconductor technology in power applications. In order to realize these applications, significant improvements has to be made in the current carrying capacity of HTSC conductors notably in high magnetic field environment. Improvement in length and performances are expected by optimizing the fabrication process making them suitable for cables and windings in prototype superconducting devices.

Our research indicates that frozen flux superconductor is possible in HTSC tapes with the incorporation of needle-like nanomagnets. These results give an alternative to the fabrications of HTSC tapes and cables for energy transport in the future.

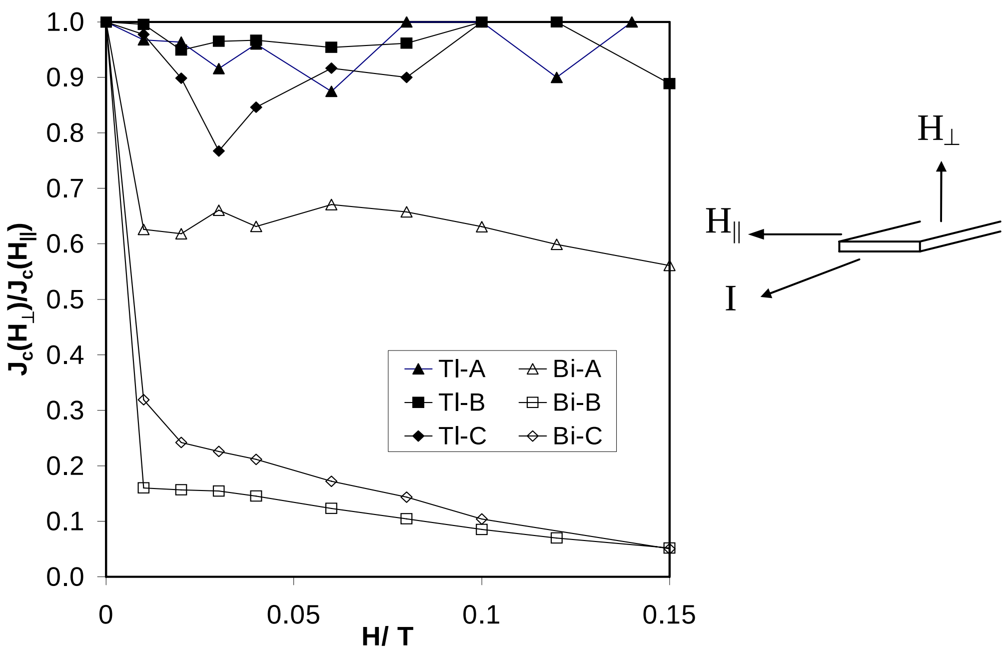


Figure 8. Anisotropy factor for Tl-based and Bi-based tapes showing the degree of anisotropy in J_c. A, B and C refers to different thermo-mechanical processes as given in [9]. Solid and dash lines are a guide for the eye.

REFERENCES

[1] Bednorz J. G. & Müller K. A. (1986). *Z. Phys. B* 64: 189-193.
[2] Wu M.K., Ashburn J.R. Torng C.J., Hor P.H., Meng R.L., Gao L., Huang Z. J., Wang Y.Q., & Chu C.W. (1987). *Phys. Rev. Lett.* 58: 908 - 910.
[3] Nagamatsu J., Nakagawa, N., Muranaka, T., Zenitani, Y. & Akimitsu, J. (2001). *Nature* 410, 63-64.
[4] Giese R.F., Runde, M., & Sheahen, T.P. (1994). Fault Current Limiters - in *Introduction to High-Temperature Superconductor* (Sheahen ed.) Plenum Press, NY,
[5] Zanella S. (2000). Power Applications of High Temperature Superconductors - in *Superconducting Materials, Advances in Technology and Applications* (Tampieri & Celotti, eds) World Scientific, Singapore, 323-330.
[6] Lyuksyutov I.F., & Naugel D. G. (1999). Modern Physics Letters 13(5): 491-497.
[7] American Superconductor Corp. (2001). http://www.amsuper.com.
[8] Nasri A-Hamid & Abd-Shukor, R. (2001). *Superconductor Science and Technology* 14(2): 113-116.
[9] Lau, K. T., Chen, S. K. & Abd-Shukor, R. (2002). *Physica C* 377(4): 547-552.