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Introduction to superconducting materials and electrical properties of their structures

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Abstract. Nowadays, with the development of our modern lives, superconducting material is closely related to our lives. Therefore, the introduction of the superconductor itself and its properties is necessary. The superconducting notion, the common superconductive substances——NbTi and Nb_3Sn——and how to manufacture the essential superconducting joint are the three parts that play the most important roles in the introduction. In this summary paper, we discuss how to make Nb_3Sn, how to create the stable and non-resistance superconducting joint, and how to measure the resistance. We find these solutions by using the document-material method and the survey method, and we summarize them for analysis of the superconducting materials. At last, the concept of superconducting materials has been discovered in this summarized thesis.

Keywords: Superconducting Materials, NbTi, Nb_3Sn, Superconducting Joint.

1. Introduction

We live in a changing world, and technology is keeping up with the times. Nowadays, superconducting materials attract extraordinary human attention, particularly with the rise of magnetic resonance imaging (MRI) in hospitals and the fabrication of magnetically levitated trains. Previous records have failed to interpret the complete concept, electrical structure, and joints of superconducting materials. Thus, these previous results are inconclusive and fragmentary. The detailed research upon superconductors' past studies led the researchers to search for a classification of comprehensive superconductive materials. Also, manufacturing qualified superconducting joints for successful use in superconductive applications and a vision for the future of superconducting materials are essential for us to understand. To address these issues, this study applies the document-material method and the surveying method to the inspection of superconducting materials. Clearly, document-material and surveying studies will be required to introduce the whole notion and the construction of superconducting materials. Schedulers who read this passage can obtain the common superconducting materials integrated and realize what should be done in future research on the superconductors. Five parts will be discussed in the rest of the paper; these studies also share a few limitations. First, the study will introduce two categories of superconductors. Second, it shows mainly the concept of NbTi, Nb_3Sn, etc.——basic substances in superconducting materials. Third, Nb_3Sn manufacturing methods are described in this essay. Fourth, the paper talks about the complete production methods of

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superconductive joints. At last, it detects the resistance of superconductivity. The conclusions and suggestions will be made at the end of the paper.

2. Type I superconductors and type II superconductors

Three factors that affect the properties of superconducting materials are temperature, critical magnetic field, and critical current. Above all, the critical magnetic field is the most important element that can most interfere with the performance of the superconducting materials. When the magnetic field decreases below a standard critical magnetic field strength Hc and then enters the superconducting state, the gain in the superconducting states can be destroyed. Hc is related to the material's temperature and matter. There is a formula that describes the relationship between Hc and the superconducting transition temperature. Tc: $\mathrm{Hc(T)} = \mathrm{Hc(0)}\ [1 - (\mathrm{T/Tc})^2]$ [1]. The superconducting materials are classified into two categories based on their magnetization properties in a magnetic field: type I superconductors and type II superconductors. All the metals besides Nb and a few elements belong to the class of type I superconductors. And one of the differences between type I and type II is that substances in type I have a critical magnetic field Hc. The superconductivity state is also called the Meissner effect, which is a characteristic feature of type I superconductors. And this effect shows that there are no magnetic lines running through the materials. Type II superconductors have two critical magnetic fields: Hc1 and Hc2. When Hc1< H0< Hc2, superconductivity state is in a mixture, which means that a few of the magnetic lines pass through the materials, and it forms a lot of cylindrical normal states with very small radii. This mixture is diamagnetic and without resistance. Nb, this element, and the alloy are the specific paradigm of Type II superconductors. NbZr, which has the same size and distribution of lattice defects as NbTi, is most likely the same. The superconducting materials can also be divided into two categories by the appropriate use temperature: low-temperature superconducting (LTS) materials and high-temperature superconducting (HTS) materials. Scientists are currently researching HTS, which could be used at high temperatures and is more relevant and practical for our lives [2].

3. Niobium–Titanium alloy and Niobium–Tin

In spite of the much higher values of high-temperature superconductor (HTS) materials at 90 K (BSCCO-2212 and YBCO-123) and 110 K (BSCCO-2223) and strong progress in developing HTS wire, these materials have not yet made a serious dent in the commercial dominance of NbTi and Nb_3Sn in the broader magnet market [3]. Nb_3Sn is the brittle compound. If a large force is applied to Nb_3Sn, the superconducting material, it will break into pieces. In order to enhance the superconductivity of Nb_3Sn, some alloying elements, such as Mg, are added to this compound. Because the Hc and Tc of Nb_3Sn are both higher than those of NbTi, Nb_3Sn is a more useful superconducting material than NbTi. But because of the structure of Nb_3Sn, this material is frangible, which is its weakness. A formula about the formation of Nb_3Sn is: $3NbCl_4 + SnCl_2 + 7H_2 = Nb_3Sn + 14HCl$. Nb_3Sn can be deposited on ceramic substrates. But in order to wind the magnet, the metal substrate must be selected for deposition. It is also an effective way to turn unstable Nb_3Sn deposits into stable copper cladding, which not only increases the stability and current-carrying capacity of the Nb_3Sn band but also decreases the transition rate from superconducting to normal. It can also protect the superconducting magnets through heat conduction. Nb_3Sn is the most potential material for use as an NMR magnet for applications requiring high Hc.

NbTi is the alloy structure. The risk of niobium non-frit was reduced by a reasonable selection of Nb and Ti elements. Three times vacuum self-consumption melting was used to create a NbTi alloy ingot with uniform composition and no Nb non-frit, as well as a large size NbTi alloy ingot with a diameter of 440mm-720mm.(1) The Ni rod is placed in the inner part of the pure Ti tube, and the pure Ti tube and Ni rod are welded together at the end of one side to obtain NbTi consumable electrode; (2) The NbTi consumable electrode is melted in the vacuum arc furnace; (3) The surface of the ingot melted in the vaccine arc furnace is skinned, and the riser is cut to obtain the NbTi finished ingot. NbTi fabrication is both inexpensive and practical. When the magnetic field reaches above 9.4T, Nb can be used as the conductor. When the magnetic field reached above 11.8T, the high magnetic inside is made of Nb_3Sn conductor. So the mixture of NbTi and Nb_3Sn is very useful while we are using that substance.

4. Niobium–Tin manufacture

As the first superconductor that proved the ability to show high nondestructive current at high magnetic fields, Nb_3Sn is described as a material that has transformed superconductivity from a scientific curiosity to an area of significant practical importance by opening the door to high-field magnet applications. Even if the last few decades witnessed the dominance of the ductile NbTi in the superconducting magnet market, in recent years, the massive use of Nb_3Sn has expanded dramatically as fields beyond the limit of NbTi are needed. During the superconducting phase of a bronze process, Nb_3Sn superconducting wire is formed by a reaction at the interface between the Nb filaments and the bronze matrix.

If Nb_3Sn was prepared by simply fusing Nb and Sn, the element ratio of the compound would be really difficult to maintain at 3:1 because the melting point of Sn is about 200 degrees and the melting point of Nb is about 2000 degrees. When they fuse, one is in a solid state, and the other is in a liquid state. And, as we know, copper can fix tin, which can then be converted into Nb_3Sn via a process known as the bronze process. Copper has a low melting point, and it is not easy to oxidize. The melting point of bronze is only 500 degrees when copper is fused with tin. The process of preparing Nb_3Sn superconducting wire by the reaction between Ni wire and bronze matrix, which is also a similar method, can be used to prepare the V_3Ga superconducting wire. Sn will have solid state diffusion, which means Sn, which was in the bronze, diffused around Ni and formed Nb_3Sn. The conduction cooling effect of copper is good and can reduce the temperature of superconducting compounds. When copper and a superconductor are connected in parallel, superconductivity is quenched because there is resistance at the Cu, which does not cause combustion. So the bronze process is a great way to produce Nb_3Sn.

The second way is the internal tin process, which is the process of preparing Nb_3Sn superconducting wire by processing Ni wire in a copper matrix with separated particles or filaments of tin or tin alloy. After the wire is processed to its final size, the tin is heated to spread throughout the copper matrix, and Nb_3Sn is generated at the interface of the Ni wire.

At last, the Powder-in-Tub (PIT) method, which means the process of loading precursor powder into silver or silver alloy tubes, spinning, forging, and drawing, and rolling to the final thickness to obtain the desired texture strip. It is often used to prepare high-temperature superconducting wire or strip. In general, the way a substance is made corresponds to its structure, and Nb_3Sn is a great example of this.

5. Superconducting joint

The core problem of the superconducting material joint is to ensure that the performance of the superconducting wire will not deteriorate after the connection, which will affect the work of the entire superconducting device. The quality of the superconducting joint is directly related to the stability of the magnetic field of the magnet quality judgment. The judgment method is that the resistance of the joint shall be as small as possible, the drop of the critical current in the joint shall be as small as possible, the joint shall have sufficient mechanical strength, and the form of the joint shall be suitable for the winding of the magnet.

Nuclear magnetic resonance (NMR) spectroscopy is an important profile. It usually uses in materials science area, and needs to operate a continuous current mode with stable time field and a lofty signal-to-noise ratio. However, there are two elements, Pb and Cd, which have the toxic metal types. Because of this poisonous property, the utilization of Pb and Cd has been extremely restricted. Also, the environmental regulations, for instance, the directive limitation of harmful substances (RoHS). The use of such materials is permitted only after the waiver has been approved, and this procedure is really costly to prepare. In addition, the utilization of these materials may be outright banned in the future. Therefore, there is an urgent need to develop new methods for realizing Pb- and Cd-free superconducting joints in industry [4].

There are two possible solutions considered to overcome the above challenges. The first solution is to develop a new type of lead cadmium superconducting soldier, based on this method, developed InSn-based alloy. Even though this material (InSn-based alloy) proved to be a potential candidate, it merely showed Hc with a maximum number of nearly 0.2 T. Moreover, no successful representations have been made so far on a superconducting joint between NbTi and Nb_3Sn wires, while both of these materials are being used.

The second solution is to solderless welding using a metallurgical reaction process. Metallurgical process of building a superconducting joint between NbTi and Nb_3Sn wires without the use of a solder is hardness to accomplish. However, this approach has not actually explored successfully due to two main factors. The first factor is the mechanics of Nb_3Sn. Nb_3Sn is an intermetallic compound with an A15-type lattice structure, which is so brittle that mechanical pressing cannot be applied [4]. On contrary to Nb_3Sn, NbTi is a body-centered cubic alloy and Ti is soluble in Nb. The solid solution NbTi is malleable and can be mechanically pressed to bond its active new surfaces to each other to create superconducting joints. The second factor is that the superconductivity of NbTi deteriorates rapidly after it reaching high temperature. The superconducting connection between NbTi and Nb_3Sn can be achieved through a chemical reaction process. In fact, we have demonstrated that the Nb_3Sn layer can form at the interface between the NbTi and Nb_3Sn wires by Sn diffusion heat treatment process. In addition, due to the degradation of NbTi properties, the transport performance of joint samples is not ideal [4]. Therefore, there is no alternative to adding superconducting solder, which becomes liquid at low temperatures, between the NbTi and brittle Nb_3Sn superconducting filaments without damage.

However, we can make the superconducting joint using some melting connection methods. The preparation process of a superconducting joint is separated into two parts: intermediate materials required (welding, fiber welding), and intermediate materials not required (cold pressure welding). First, the fiber welding connection is that the melting fiber, with a melting point lower than the annealing temperature of the superconducting material, will fill the gap of the conductor joint with capillarity, and a metallurgical reaction will occur. Joints are divided into two sections: the lap joint and the bridge joint, and the bridge joint is divided into a parallel bridge joint and a vertical bridge joint. Under the same conditions, the larger the contact area is, the smaller the resistance of the joint is, and the resistance of the parallel bridge joint is smaller than that of the vertical bridge joint. Also, the direction of the auxiliary belt has an impact on the joint characteristics. The resistance of the lap joint is smaller than that of the bridge joint. Although the resistance of the lap joint is generally less than the resistance of the bridge joint, the connection mode of the bridge joint has little influence on the magnetic field distribution. It is suitable for the connection between the double pancake coils of the high temperature strip magnets, that is, the connection of the high-temperature strip. However, due to the influence of contact resistance, fiber welding does not completely form metallurgical bonding at the interface, so the resistance of fiber welding joints is generally large.

Second, the diffusion welding connection is that the welding device is placed in a vacuum or protective atmosphere, applied with appropriate pressure, and then heated to a temperature lower than the superconducting heat treatment temperature for a certain period of time. The essence is metallurgical bonding by means of atomic diffusion. Diffusion welding can achieve a very low joint resistance value, which can effectively avoid the performance degradation caused by the process, and adding silver tape in the middle of the joint can improve the electrical and mechanical properties of the joint. Suitable for high-temperature strips. Diffusion welding is a time-consuming process that requires a stable low temperature and pressure at both ends of the strip. Nitrogen environments are currently a more promising method.

Third, fusion welding connection means that we soak the wires to be welded together in the molten solder and connect the superconducting wires when the solder cools. This method is applicable to multiwire connections. The process of fusion welding includes the process of matrix material replacement, which can make the wire to be welded more fully in contact with the solder in the process of fusion welding so that the joint resistance value of the fusion welding process is very small, which is applicable to low-temperature wire. But there are also disadvantages: The resistance of the joint is affected by the critical characteristics of the solder, and the solder is very sensitive to the influence of the background magnetic field.

Fourth, there is the cold pressure welding connection. Under room temperature, pressure causes plastic deformation at the welded part, causing the welded contact surface to come into close contact, and the welded part to be welded together by the mutual diffusion of molecules and atoms. This method has a simple preparation process and small joint resistance, but the cold pressure welding process is only applicable to LTS wire. However, HTS tape is not suitable for this method because of its fragile material.

And at last, there is the sintering connection. It is a material chemistry method that uses appropriate materials to fill the joint position and directly conducts processing at the crystal absorption temperature. This method can make the texture of the joint similar to that of the base metal from a microscopic perspective, so that the grain boundary out of the joint is approximately eliminated. Its superconducting property can be similar to that of the base metal, and the resistance of the joint can be very small. However, this method is really tough. The powder ratio at the connection part is very high, and the crystal absorption process is complex. At present, this method is only tested in the laboratory and is not widely used [5].

6. Measure superconductors resistance

There are two methods to measure the superconductors' resistance: the four-point method and the coil current attenuation method. By comparing these two ways, we could find that the coil current decay method can reach a higher measurement precision of up to 10-13 Ω or 10-14 Ω. This method is dependent on the fact that the current decay in a loop connected to a joint is due to the joint resistance. It could be considered that in the persistent mode, the superconducting nuclear magnetic resonance magnet (NMR) has a high requirement for tiny joint resistance, so we choose the coil decay method most of the time to measure joint resistance [5].

7. Conclusion

In this article, we have attempted to explain the basic knowledge about superconductors, including superconducting categories, how to manufacture one of the common superconductors——Nb_3Sn, how to make superconductive joint, and how to measure the resistance of the superconductors. Also, there are some items surrounding the superconducting applications. Our viewpoints are based mainly on the document-material method, using a large amount of recent research and survey studies, which conclude the paper. The first point of the paper is that there are three factors that affect the superconducting properties: temperature, critical field, and critical current. And on account of the common use of superconductors, researchers are investigating high temperature superconductors. The research provides some insights into Nb_3Sn characteristics and its manufacture methods, including the bronze process, the internal tin process, and the powder-in-tub (PIT) method. Also, there are five common methods to connect the superconducting joints: fiber welding, diffusion welding, fusion welding, cold pressure welding, and Sintering connection. Finally, there are two ways to gauge the resistance: the four-point method and the coil current decay method.

Consequently, there are still some limitations to this study, which could lead to further studies and verification for future directions. In this research, we find that Nb_3Sn has the capacity to have a high lossless current at high magnetic fields, but because of its interior construction, Nb_3Sn is the brittle compound and is vulnerable. Although the price of NbTi is lower than that of Nb_3Sn, the range of applications for NbTi is narrower. And both of the superconductors are low-temperature superconductors, which means we should give them extra energy to keep the temperature at low degrees. Furthermore, empirical studies or experiments should be conducted for verification of our idea and the introduction. At the present state of knowledge, however, there are some important lessons for practice and research. Scientists can find an accurate way to combine NbTi and Nb_3Sn, mixing the advantages of both materials, and manufacture the best-performing superconductors. Perhaps they could also find a new superconducting substance or compound that can be used at room temperature. And we can save a lot of energy and money after this discovery is made.

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