Development of Electromagnetic Forming NbTi Superconducting Joint

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***Abstract*—An extreme low-resistance NbTi superconducting wire jointing technology is a key issue for the construction of the scientific superconducting magnet that required high field stability. In this paper, a novel electromagnetic forming NbTi superconducting joint technology was developed. The preliminary experiment was done, and the fabrication technique was researched by changing the parameters. The joint resistances were tested using the coil current decay method. The contact resistance properties of the superconducting joint were investigated. The induced magnetic field and electromagnetic force, plastic deformation, and the electrical contact characteristics of the NbTi superconducting joint were discussed. The preliminary results show that the electromagnetic formed NbTi superconducting joint has excellent electrical interconnection property and easy operation.**

***Index Terms*—Electrical resistance, electromagnetic forming, NbTi, superconducting joint.**

I. Introduction

Superconducting precision instruments, such as NMR, MRI, FTICR-MS, and some inertial navigator, need an extremely stable magnetic field [1]. Generally, the field stability of a magnet is mainly affected by the resistance in the coil circuit and inductance, especially by the wire joint resistance. It is necessary that the resistance of the superconducting joints be extremely low for the persistent current decay. For instance, a 400 MHz NMR magnet with the inductance of 92.2 H, having ten joints, requires that the maximum resistance tolerance for each joint must be less than $2.56 \times 10^{-11}\ \Omega$ [2]. For the NbTi superconducting alloy multi-filament wire being widely used almost every one magnet, many jointing methods have been developed [3]–[9]. Among them, the soldering and welding are commonly used. However the exiting solder composition limits its application range only lower than about 5000 Gs background field. Cold-pressing is not influenced absolutely by the solder composition for its physical processing. The joint may endure the background field as high as 2 T. The minimum resistance may reach as low as $8 \times 10^{-13}\ \Omega$ [2]. This resistance value is low enough to be satisfied with demand of the decay rate of 1 Hz/hour of the 400 MHz NMR magnet. But researchers found that there are oxide layer and residual Cu-rich particles at poorly bonded interfaces in the cold-pressing joint respectively by SEM and EDX [10], [11]. The oxidation film prevents the metallurgical bonding between the superconducting filaments for its nonmetallic property. Then the exiting cold-pressing jointing method is absent of reliability. In order to enhance the electrical resistance performance of cold-pressing joint, a new jointing method should be developed to destroy the oxide film and enhance the joint electrical performance.

Electromagnetic forming (EMF) technology is based on the Faraday's law of electromagnetic induction resulting in repulsive Lorentz body forces between two conductive bodies carrying opposed currents. It is a high speed metal forming system where the workpiece is accelerated by a pulsed electromagnetic force [12]–[14]. Typically, the pressures at the collision point between the mating surfaces are in the range of 15 Mpsi. It has been widely applied in a variety of geometric arrangements including tube expansion or compression and a variety of sheet forming methods [15]–[19]. The EMF is seldom researched in the superconducting jointing process. The Nb_3Sn/Cu splice was manufactured by EMF method for horizontal racetrack damping wiggler magnet [20]. The copper matrixes of two parallel Nb_3Sn wire was connected by EMF. The reduction of resistance is very limited because of the Nb_3Sn conductors not realizing the metallurgical bonding in the joint. The MgB_2 joint was also fabricated by packing magnesium, boron and copper powders inside a copper tube between the wire ends with electromagnetically assisted technique and then heat treatment [21]. The resistance only reached $6.6 \times 10^{-10}\ \Omega$ at 4.2 K and zero background field. Actually, the plastic material, like as superconducting NbTi alloy, is more suitable for the EMF processing.

This paper was focused on the EMF technology being applied to the NbTi superconducting wire jointing processing for its advantages of high efficiency and repeatability. The relationship between the initial voltage and the joint resistance was discussed. The purpose is to find a novel method to overcome the disadvantage of the exiting jointing methods.

II. Experimental

A. Electromagnetic Forming System

A type of standard EMF system was used in this experiment. The equivalent discharge circuit was shown in Fig. 1(a). This

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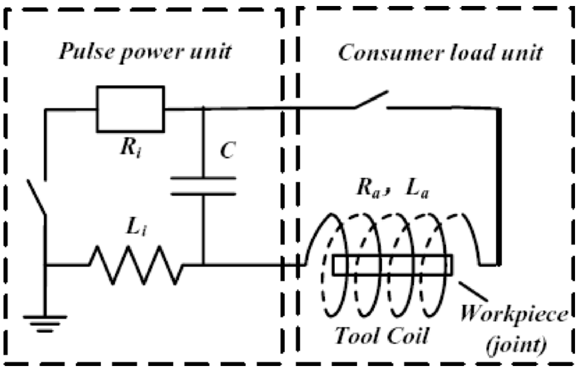
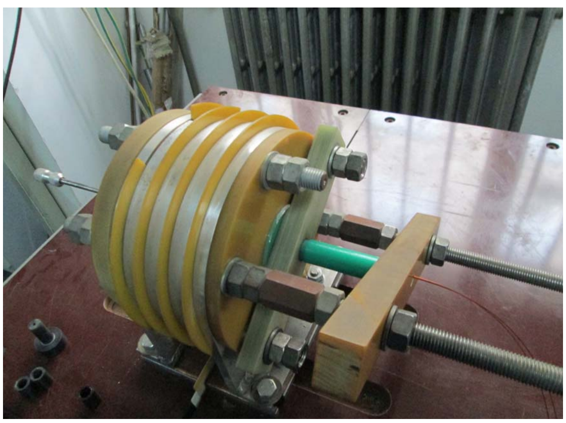


(a)



(b)

Fig. 1. (a) Equivalent discharge circuit and (b) general view of the tool coil with workpiece (joint).

TABLE I
PARAMETERS OF THE EMF SYSTEM

Parameters	Value
energy storage	20 *kJ*
maximum voltage	8.5 *kV*
normal operating voltage	⩽7.5 *kV*
maximum discharge current	600 *kA*
normal discharge current	⩽400 *kA*
charging time	1.75 *kJ/sec*
capacitance	553 μF
inductance	30 *nH* ±10%
discharge frequency	40 *kHz*

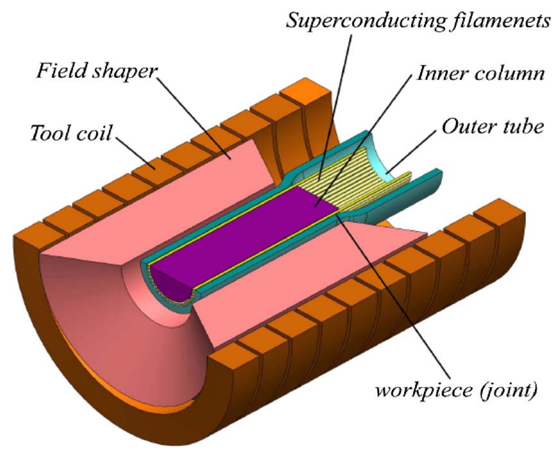


Fig. 2. Arrangement of tool coil, field shaper, and workpiece (joint).

EMF system is mainly made up of both the pulse power unit and the consumer load unit. The former is used to generate pulse power, consisting of the energy storage with capacitance C, a high current switch, and the energy conduction system (Resistance R_i and Inductance L_i). The later is to encourage the coil to enforce the workpiece happening deform. Its components include both exchangeable tool coil and workpiece to be deformed. The arrangement of tool coil with experimental workpiece (joint) was shown in Fig. 1(b). As a tubular workpiece, the joint can be compressed by the tool coil which is located around the workpiece, with resistance R_a and inductance L_a. By discharging the capacitor, a high magnetic flux density is generated, initially located in the gap between windings and workpiece. According to Lenz's law, a current density is induced into the tube which causes, in combination with the flux density, a body force distribution in the specimen, known as Lorentz force that, in turn, causes it to deform. In this experiment, joint fabrication was carried out on a Pulsar MPW 20-9 machine and the experimental conditions were shown in Table I. The EMF system has the ability of maximum accumulation energy of 20 kJ, initial operation voltage of 7.5 kV and discharge frequency of 40 kHz.

B. Preparation of Joint Assembly

The multi-filament superconducting alloy wire for experimental joint was adopted from Oxford Superconducting Technology. The nominal diameter of the wire is 0.60 mm. It contains 54 NbTi alloy filaments that be surrounded by copper matrix. The ratio of copper to superconductor is 1.35. The residual resistance rate is larger than 70.

The arrangement of tool coil, field shaper and experimental workpiece (joint) was shown in Fig. 2. The joint assembly consists of the copper outer tube and the NbTi alloy inner column. The copper outer tube is 14 mm in inner diameter, 16 mm in outer meter and 34 mm in length. The small wall thickness ensures easier deformation. The NbTi inner column is the diameter of 12 mm and the length of 50 mm. There is a narrow gap of 1 mm between the inner column and the outer tube. The NbTi alloyed multi filaments were arranged in the gap between the NbTi inner column and the Cu outer tube. The copper tube will be compressed and the gap will disappeared under the electromagnetic force. In order to place the two NbTi wires to be jointed, a rectangular groove with 1.0 mm in breadth and 0.4 mm in depth is cut on the surface of the NbTi column die along the axial direction.

The inductive tool coil has 4.5 turns. Its bore has the inner diameter of ~73 mm and the length of ~70 mm. There is a large interval of 28 mm between the tool coil and the joint, considering the outer meter of copper outer tube is only 16 mm. The large interval would greatly weaken the electromagnetic force on the copper outer tube. Then, a type of copper field shaper was designed to focus the magnetic field to a work zone of 10 mm in length and 17 mm in diameter. Finally the gap was reduced to 1 mm. Besides, the field shaper was slitted as

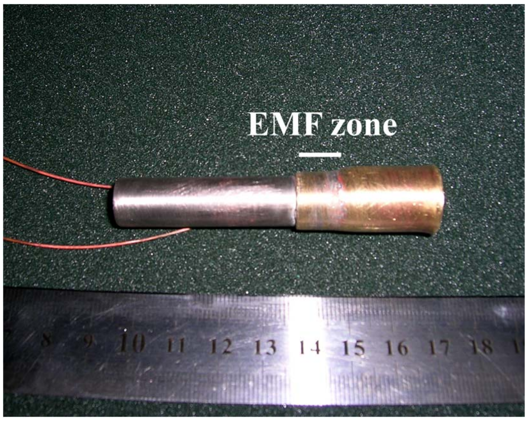


Fig. 3. Configuration of joint made by EMF method.

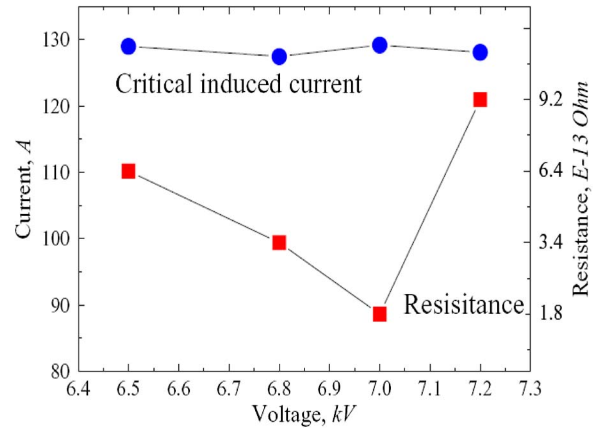


Fig. 4. Critical induced current and resistance versus initial voltage of joint made by EMF method.

1 mm along the radius. Compared to the outer surface of the field shaper, the concentration area is much smaller, resulting in a higher current density and higher magnetic field here.

C. Jointing Procedure

The manufacturing process of NbTi alloy superconducting joins was divided into several steps as shown as follow:

i) Remove the copper matrix of the wire by acid solution until only a brush-like bundle of NbTi filaments was left.
ii) Clean and dry the filaments and the joint assembly.
iii) Put all filaments into the rectangle groove of NbTi column die and then set the copper tube outside them.
iv) Take the joint assembly to the EMF system and install it at center of the tool coil.
v) Operate the power supply to charges the energy storage, then close the spark gap switch causing a damped oscillating current through the tool coil. Then an induced electromagnetic force causes the copper tube deforming and the NbTi alloy filaments are embedded tightly in the tube to form the joint. Configuration of joint made by EMF method was shown in Fig. 3. The EMF bonding zone was marked out.

D. Testing Apparatus

The resistance and the critical induced current of joint sample were measured by coil current decay method under liquid helium conditions [2]. This method is to measure the decay of the magnetic field produced by the current induced in a superconducting loop which includes a joint. The test system, which consists of a current transformer, a background field coil, a cryogenic Hall probe and a small loop to be tested, had been set up in our laboratory. The cryogenic Hall probe is with type of model HGCA-3020 from Lakeshore.

III. Results and Discussion

A. Experiment Results

For EMF system, the operation voltage is the most direct reflection of the input energy. In order to evaluate the joint quality, four joint samples were made under variety initial discharge voltage from 6.5 to 7.2 kV, respectively. The testing results are shown in Fig. 4.

It is clear that the critical induced currents of the joints all keep around 129 A. The maximum value of the critical current of 129.2 A is from the joint with the initial discharging voltage of 7.0 kV. The minimum value of 127.5 A is from that of 6.8 kV. The stabilization of the critical induced current indicates that the superconducting filaments were not harmed with the increasing of the electromagnetic force during EMF jointing procedure.

It is also found that the joint resistance value is affected obviously by the initial voltage. Firstly, the joint resistance decreased almost linearly from 6.4×10^{-13} Ω alone the initial discharging voltage rising from 6.5 kV. Subsequently, the resistance reached the minimum value of 1.8×10^{-13} Ω when the voltage is 7.0 kV. But after that, the resistance increased suddenly to 9.2×10^{-13} Ω with the voltage continually rising to 7.2 kV. It seems that the resistance of the joint would be worse when the initial discharging voltage is over a certain criterion. It may be attributed to the discharging energy being so large over than the plastic limit strength to harm the tube and/or the filament. Therefore, the resistance of the joint was affected negatively.

B. Discussion

Although the EMF processing is with the advantages, such as high strain rates plastic deformation, self-cleaning surface, high bonding force, contact-free, no-lubricant, good repeatability and high production rate, the EMF superconducting jointing method is such a novel solid welding technology that the plastic deformation mechanism around the weld zone are still being discussed frequently. In fact, the solid welding process induced from electromagnetic pulse accelerating may be described in the plastic deformation dynamics. The high-velocity impact causes the high strain rates plastic deformation. The material behaves like a high viscosity fluid although it remains solid. The bonding mechanism may be transferred from investigations considering explosive welding and cladding [22]. In field of surface physics, realization of solid bonding needs to meet two conditions. One is the surface is clean; the other is that the surfaces of the couple should be near enough to under the pressure. The oxide films on the filament and tube really prevent

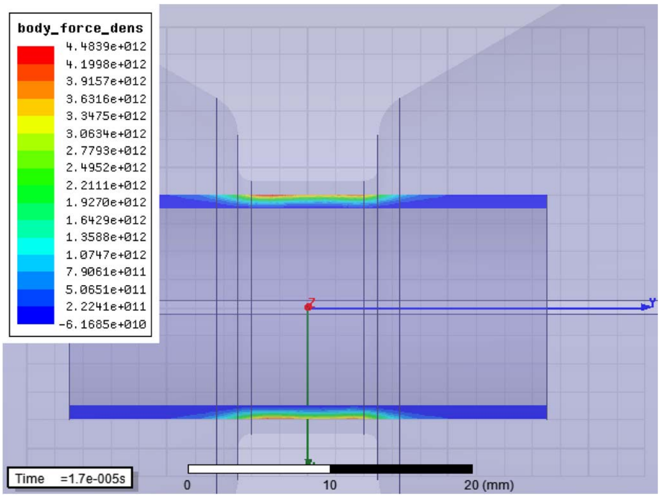


Fig. 5. Induced body force density on the surface of the out tube.

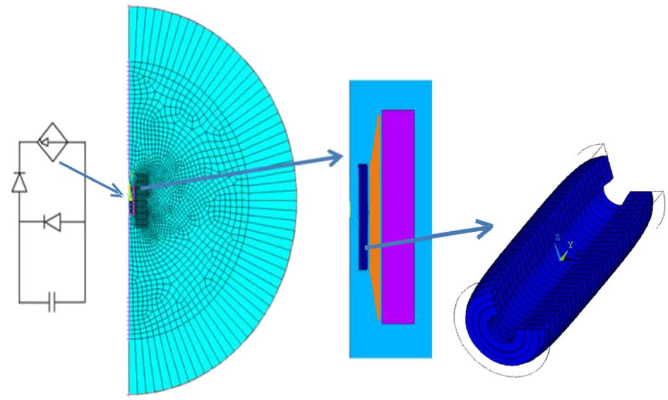


Fig. 6. Out tube deformation of EMF NbTi joint using FEA simulation.

the resistance reducing. It is just the reason of the resistance of the cold-pressed joint cannot be reduced more.

The EMF pulse charging circuit and the discharging process were modeled and simulated using electromagnetic software. The calculation results showed that the peak current of the tool coil, charged by the pulse power unit, would reach 380 kA under the condition of 40 kHz in discharge frequency and 7.3 kV in operating voltage. Then there would be generated a $\sim$67 T instantaneous magnetic field and a subsequent induced current as high as 7.69×10^{10} A/m^2 on the surface of the outer tube. Under the effect of electromagnetic induction, the instantaneous maximum body force density on the tube surface would reach 8×10^{12} N/m^3, as shown in Fig. 5. Under the conduction of such enormous induced electromagnetic force, the drastic plastic deformation of the outer tube was happened and then the NbTi superconducting filaments were pressed tightly on the column.

Also, a preliminary numerical simulation was carried out to simulate the joint deformation, as shown in Fig. 6. The tube deformation was calculated using the direct electromagnetic-structural coupling algorithm. The results show that the joint tube would shrink alone the radius direction. The both ends of the joint tube would shrink worse because of less restriction. In next step, the superconducting filaments deformation situation will be calculated by adding the tube deformation as displacement boundary condition using finite element analysis method.

As to EMF processing, it was known that collision direction of the workpiece couple is not vertical but as an oblique impact with a slip angle. The collision impact is helpful to the jet being like fluent [23], [24]. The jet is created between the two bonded surfaces by the impact force acting upon them. The jetting action might not only removes the oxide film and surface contaminants, but also make the surface become more uneven to enhance the contact area. The result is that two virgin surfaces was pressed together under very high pressure, bringing the atoms of each metal into close enough contact with each other, to allow the atomic forces of attraction to come into play. As a result, the EMF joint with the solid welded surface has the better electrical quality than exiting cold pressing joint.

The EMF joint length is only 10 mm as shown in Fig. 2, comparing with the cold-pressed joint with length of 30 mm. Its resistance is as low as the 20% of that of the cold-pressed joint.

IV. Conclusion

The preliminary experiment of electromagnetic formed NbTi superconducting joint was done. The fabrication technique was researched by changing the parameters. The plastic deformation of the fabricated joint was investigated. The contact resistance properties of the superconducting joint were investigated. The induced magnetic field and electromagnetic force, evolution of plastic deforming and the electrical contact characteristics of the NbTi superconducting joint were discussed. The test results show that the maximum value of the critical current is 129.2 A and the resistance is the 1.8×10^{-13} Ω when the initial discharging voltage is 7.0 kV. It means that the electromagnetic formed NbTi superconducting joint has the excellent electrical conductivity, low resistance and easy operation.

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