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CONTACT SURFACES BETWEEN STRANDS OF RUTHERFORD CABLES IN VARIOUS CURING CONDITIONS

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ABSTRACT

Interstrand AC losses and contact resistances of Rutherford cables are easily affected by curing conditions. We have measured the interstrand AC losses and contact resistances for three kinds of Rutherford cables, made from strands with a Cu matrix, a CuMn barrier around a filamentary bundle and a CuMn matrix inside a Cu sheath. The losses of all the cables were relatively large under a condition without release of pressure after curing. They were significantly reduced after releasing the pressure at a room temperature except for the cable with a Cu matrix at a high curing temperature. The measurement of contact resistances show the same dependencies. Strands of the cable with a Cu matrix were bonded at crossover points by curing at higher temperature, and bonded crossover points were not broken when pressure is released after curing. We have also observed contact surfaces of the strands by using a Scanning Electron Microscope, and found that there were traces of diffusion bonding on the contact surfaces. Main roll why the other cables show smaller AC losses by releasing pressure can be explained by the mechanical properties of the matrix materials.

INTRODUCTION

Superconducting dipole magnets for high energy accelerators fabricated with similar Rutherford cables have shown quite different behavior of quench current degradations with di/dt .¹ They are distinguished into two categories. One of the degradation behaviors becomes larger and larger according to increase of ramp rate, and the other shows larger degradation in lower ramp rate and almost no degradation even in higher ramp rate. The former degradation can be explained by interstrand AC losses in the superconducting cables. The latter might be caused by current sharing phenomena between cable strands.

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Many studies have been performed on AC losses of Rutherford cables.^{2 - 7} It is, however, not clear why the ramp-rate dependencies vary over a wide range from magnet to magnet. Coils of these magnets have usually been fabricated by heating under pressure to fix with epoxy resin called *curing* process. From the previous studies,^{8 - 10} we have obtained the following results: first, the interstrand AC losses of cables strongly depend on curing temperature over 180 °C in case of a cable with a Cu matrix, and second, cables with a CuMn matrix or barrier have shown weak curing-temperature dependencies below 230 °C, but strong dependencies over this temperature. In these AC loss measurements, samples have been cured under pressure, removed from a curing fixture and measured in another fixture in order to simulate an actual curing process. We have noticed pressure release in the curing process and the mechanical properties of cables may be one of the most important factors to control the interstrand AC losses. In order to clarify the mechanism of the AC losses, we have prepared three types of cables, and measured AC losses, crossover resistances and mechanical properties of the matrix materials.

This paper describes the experimental results of these measurements and discussions of the interstrand AC loss mechanism.

EXPERIMENTS

Measurement of Interstrand AC Losses

Three types of Rutherford cables, which are used for high energy accelerator magnets, have been investigated in order to clarify the mechanism of the curing temperature dependencies of interstrand AC losses. The parameters of the cables are given in Table 1. They have essentially the same as those for the SSC dipole magnets. Cables s1 and s2 have NbTi filaments of 6 μm in a Cu matrix. Cable s2 has a CuMn barrier of around 10 μm thick between a copper sheath and a filament bundle. Cable s3, which was specially developed for the SSC HEB dipole magnets, has thinner filaments of 2.65 μm in a Cu/CuMn matrix. The CuMn matrix of about 0.5 μm thick is placed around each NbTi filament in order to reduce the proximity effect. These cables are insulated with a 25 μm polyimide film half-lapped and a 50 μm film with a B-stage epoxy resin.

We have treated the cables from the temperature of 120 °C to 300 °C under pressure of 50 MPa. The samples moved from a curing fixture by releasing pressure to AC loss measurement equipment. The sample with a Cu matrix shows relatively large temperature dependencies of the AC losses as shown in Figure 1. The interstrand AC losses of the sample increase three orders of magnitude when it is cured at 230 °C. On the contrary, the samples with CuMn inside show small temperature dependencies. We can see that the increase of the losses at 230 °C is only a few times.

We have measured also the same cables with keeping pressure during the whole curing and measurement processes. In this case, even for the CuMn matrix and barrier cables, they show very large interstrand AC losses even with low temperature curing. The effect of the pressure release is more apparent for the cables with CuMn and is smallest for the cable with a Cu matrix over 200 °C. The decrease of the losses by pressure release for the sample with a Cu matrix at 230 °C is only one order of magnitude. It shows still large interstrand AC losses.

Table 1. Parameters of cables.

Cable ID	s1	s2	s3
Number of strands	30	30	30
Strand diameter (mm)	0.808	0.808	0.808
Filament diameter (μm)	6	6	2.65
Matrix	Cu	Cu/CuMn (Barrier)	Cu/CuMn
Cable width (mm)	12.125	12.125	12.34
Mean thickness (mm)	1.458	1.458	1.458
Transposition length (mm)	86	86	86
RRR of copper	140	70	120
Insulation thickness (μm)	100	100	100

Figure 1. Interstrand AC losses for three types of cables keeping and releasing pressure.

Measurement of Crossover Resistances

The interstrand AC losses of the stranded cables are given by Morgan² as follows,

$$W = \frac{N^2 h^2 L}{60 R_c} B$$

where N is number of strands, h the width of cable, L the cable transposition pitch and R_c the crossover resistance. The measurement of crossover resistances for the curing cycle conditions will give us another information about the mechanism of the interstrand AC losses.

In the measurement of crossover resistances using longer cables, measured values give averaged resistances because there exist many crossover points in the samples. In order to measure actual values and their distribution along the cable width, we limited the sample length only to 4 mm. In this length we can detect the localized crossover resistances which include only one and three crossover points as shown in Figure 2. Three strands on one face of a cable (center and edges) were selected and measured crossover resistances between three strands on the other face by using a 4-wire method. The samples were fixed with a fixture and cured under pressure of 50 MPa.

Figure 2. Measurement scheme of crossover resistances.

Table 2. Measured crossover resistances ($\mu\Omega$).

Temp.(°C)	Cu	CuMn Barrier	CuMn Matrix
150	<u>9.5</u>	<u>54.6</u>	
	78.6	1082.2	
230	<u>0.3</u>	<u>10.7</u>	<u>3.0</u>
	4.8	217.8	38.2
300	<u>0.04</u>	<u>0.36</u>	<u>0.17</u>
	0.70	1.04	3.24

under pressure
release pressure

The crossover resistance measurements for the three samples have been performed by keeping pressure. After the measurement the same samples were released pressure once and then measured under the same pressure as one at curing. The measured results were given in Table 2. Releasing pressure affects increase of the crossover resistances for all samples at low curing temperature. For the Cu matrix sample, however, the increase of the crossover resistances by the pressure release is much smaller than those of the other samples at 230 °C. This tendency vanishes for all the samples in case of curing at 300 °C.

We have also measured the crossover resistances of the Cu matrix cable depending on curing time under the same curing conditions. The same sample was cured every 10 minutes and measured the crossover resistances by keeping pressure as shown in Figure 3. Data in the figure show the resistance distribution along the cable width. The sample cured at 120 °C gives relatively large scattered and constant resistances with the curing time. On the contrary, the sample cured at 150 °C shows scattered data in the shorter curing time but dramatically decreased and focused onto the same value at curing time of 20 minutes. This phenomena are also apparent higher curing temperature than 150 °C.

Observations of Contact Surfaces

We have observed the surfaces of the cured samples at various conditions by using a Scanning Electron Microscope. There are many scratches on surfaces of strands due to wire drawing processes before curing. After curing, surfaces of crossover points of strands called *spoon* would be expected to become smooth. It can be, however, imagined that metallic bonding may be formed at higher curing temperature and rough surfaces may be observed on spoons by breaking the bonding. The typical pictures are shown in Figure 4. In the figure, the picture (a) and (b) are surfaces of spoons for samples with a Cu matrix.

Figure 3. Curing time dependencies of the Cu matrix cable.

(a)

(b)

(c)

(d)

Figure 4 Pictures of the contact surfaces of the three samples. (a) and (b) are for the cable with a Cu matrix cured at 120 and 300 °C, respectively (x 2000). (c) and (d) are pictures which show evidence of torn surfaces on spoons for the cable with the CuMn barrier cured at 300 °C (x 800).

Picture (a) shows a surface of a spoon cured at 120 °C, and (b) one at cured at 300 °C. It shows a very rough surface at 300 °C in comparison with one at 120 °C.

The lower two pictures (c) and (d) show surfaces of spoons which contacted each other in one-to-one for the sample with a CuMn barrier cured at 300 °C. It can be clearly distinguished that the pattern at the lower part of the picture corresponds to the other. They show an evidence that they were torn off from each other. We could find out many torn traces from spoons not only the samples with a Cu matrix but ones with a CuMn matrix or barrier. The rough surfaces of the spoon of the samples mean broken contacts.

DISCUSSION

The Rutherford cables show the largely scattered interstrand AC losses according to the curing temperature. From the previous study the samples with a Cu matrix logarithmically increase the interstrand AC losses above the curing temperature of 180 °C even when pressure is released.⁸ We have also investigated the dependencies of the losses on various curing conditions, those are curing temperature, curing time, and curing pressure. Those measurements will be reported in other materials. From the results the

interstrand AC losses strongly depend on not only curing temperature, but also curing time and pressure above 180 °C. Below 180 °C the interstrand AC losses have almost no dependencies on the curing conditions. On the other hand, the samples with a CuMn matrix or a CuMn barrier have not shown these dependencies below 230 °C. Those are the case that pressure is released.

The crossover resistances, which were measured by keeping pressure from curing through measurement, show relatively small values even for the samples with CuMn alloy.¹⁰ After the pressure was released at the room temperature, the increase of the crossover resistances is remarkable and consistent with the measurement of the interstrand AC losses.

From the observations of the surfaces of spoons, they were very rough before curing, because strands were strongly deformed and mechanically scratched in a manufacturing processes. After curing the surface became smooth due to plastic deformation or creep flow of Cu. In higher curing temperature above 230 °C it was clarified that the contact surfaces became rough again but different from original surfaces by our observations. We could see many evidences of broken surfaces in spoons. This fact gives that the surfaces of the strands at crossover points were bonded with each other. This process in a low temperature should be a diffusion bonding.

Strands of Rutherford cables are strongly deformed by other strands in a compacting process at manufacturing and spoons are formed on the surfaces of strands at crossover points. We have found that there were two concentrically elliptic areas on the spoons. The inside ellipse was deoxidized and outside one oxidized after curing, and moreover the inside elliptic region was enlarged according to increasing curing temperature.

In the field of welding, an early stage of diffusion welding was investigated for several kinds of pure metals including copper.¹¹ An oxide film on surfaces of metals was one of the most important factors which prevents true metal-to-metal contacts on the bonding surfaces. The oxide film on an intimate contact zone disappears, forming inclusions owing to spheroidizing of the oxide film. The amount of inclusions decreases owing to diffusion of oxygen during welding. The temperature to start diffusion welding is same as disappearance of the oxide film. This temperature corresponds to the softening temperature of metals which we have measured for pure copper (OFC) and CuMn alloy. From the results, the softening temperatures are about 150 °C of Cu and 300 °C of CuMn. The softening temperatures are easily affected by the purity and treatment history of the materials. The results support to initiating temperature of a diffusion bonding. Recent measurement of interstrand AC losses for cables in which resistive films were set also suggests the possibility of the diffusion bonding.¹²

Since the CuMn alloy has stronger mechanical properties than copper, it will play a role on resistive force to deform the contact surfaces at the curing temperature below 230 °C. This means that the bonding area is smaller and bonding force is weaker than that in case of the cable with a Cu matrix. Therefore, in the samples which are released pressure after curing, the diffusion bonding is broken and the samples show relatively large crossover resistances.

CONCLUSION

The following items have been clarified by investigating the curing temperature dependencies of the crossover resistances for a few kinds of the Rutherford cables related to the interstrand AC losses.

- (1) The crossover resistances which are related to the interstrand AC losses are mainly affected by the mechanical properties of the composite materials of the matrices.
- (2) At the contact surface between strands Cu diffuses and the surfaces bond with each other during curing process over 150 °C.
- (3) When the pressure on the cable samples is removed, the mechanical spring-back forces remove the contact surfaces, and increase the crossover resistances due to oxide layers and roughness of surfaces.
- (4) The CuMn alloy in a matrix or a barrier is resistive to deform contact surfaces below 230 °C and then decreases the contact area and the bonding forces between strands.

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