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Analysis of the DC Resistance of the Butt Joint using the Random Contact Patterns of Strands

Ho-Jin Lee, Sang-Il Lee*, and Bong-Sang Lee

Korea Atomic Energy Research Institute, *KBSI

Hjlee1@kaeri.re.kr

Abstract-- **The butt joint was verified to satisfy the thermal stability of the ITER magnet system through the ITER CS model coil test. Since the contact area in the butt joint is limited to the cross section of the cable, it is necessary to analyze and control the joining parameters precisely for improving the DC resistance. It is difficult to simulate the cables, which are composed of a lot of strands, as three-dimensional models using the commercial code. The random numbers were used to simulate many kinds of contact patterns of the strands on the bonding surface for calculating the bonding area and the DC resistance of the butt joint. The calculated DC resistance decreases with an increase of cable filling factor in terminal. The calculated DC resistance of a 0.9 cable filling factor is about 0.48 n-Ohm, which is about one-tenth of that in the CS model coil test when not considering the electrical contact resistance. From this difference, the electrical contact resistance between the strands and copper sheet was calculated.**

1. INTRODUCTION

Conductor joining is one of the key technologies for superconducting coils. When the transport current crosses the interface between the two superconducting conductors, there are almost always a generation of heat and a deterioration of joint properties. Because the operating condition of the recent superconducting magnets is severe, a small sized joint having a low resistance and low ac losses is needed to stabilize magnet system [1,2].

A butt joint has been considered as a suitable joint to use in the zones of a high field and a high field change, because it has low AC losses. The joining area in the butt joint is small compared with the conventional type of joints such as lap joint [3]. The technology for reducing the DC resistance of the butt joint has been developed through the ITER coil research. The compacted terminals of Nb_3Sn conductors are connected by diffusion bonding to increase the bonding strength and to decrease the DC resistance. The DC resistance of 3.2 n-Ohm was measured in the butt joint of the ITER CS model coil, and this value was considered low enough to use for ITER device [4].

The effective joining parameters for reducing the DC resistance of the joint were investigated through many experiments without analysis. It has been reported that the low DC resistance could be obtained when changing the twisting patterns of sub-cables in CICC (Cable-in-Conduit -Conductors) [4].

Analytical expectation of the variations of the DC resistance by changing the joining parameters before the experiment is a good method to decrease the trial numbers of the experiment. Three-dimensional modeling by the commercial codes may have some problems, because the strands in the cable are too many to simulate and the contact patterns of the strands on the bonding surface are too various to expect. In this research random numbers are used to simulate the many kinds of contact patterns of the strands on the bonding surface of the joint. Through many times of calculation using random numbers, the DC resistance and bonding area were anticipated. The effect of cable filling factor in CICC was analytically investigated to anticipate the variation of the DC resistance and the bonding area of the joint.

2. BUTT JOINING PROCESS

Fig. 1 shows the schematic drawing of the butt joint, which connects electrically two CICC terminals directly without an overlapping of the conductors. Because of its small size, the ac losses are sufficiently small compared with conventional lap joint. As shown in Fig. 1, the joining area between the two terminals is limited to the cross section of the terminal. Diffusion bonding method is used instead of soldering to decrease the electrical contact resistance and to increase the bonding strength of the joint [2].

The cable filling factor, which is the fraction of the cable filling space bounded by the interior wall of a terminal, is controlled by compaction of the cable inside the copper sleeve after removing the jacket of CICC. After a reaction for superconductivity, two contact surfaces are finely ground and loaded against each other with heating the joint at 750 °C for 1 hour.

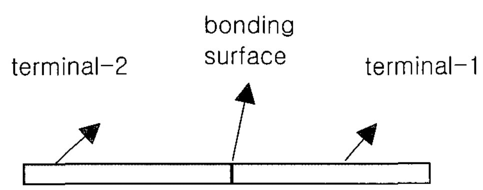


Fig. 1. Schematic drawing of the butt joint.

In this process, the diffusion bonding occurs between the strands on the bonding surface of two terminals with various contact patterns. Between the two terminals, a copper sheet of a 0.1 mm thickness is inserted to increase the bonding area and strength, because the diffusion bonding occurs between coppers in the cable. The cable filling factor in the terminal is considered as a main parameter of the DC resistance. The DC resistance and the bonding strength of the joint can be expected by analyzing these contact patterns of strands on the bonding surface.

3. MODELING OF THE BUTT JOINT FOR CALCULATING THE DC RESISTANCE

3.1. Modeling of the distribution of the strands in the cable

The distribution of the strands in the cable is first assumed before modeling the butt joining. The cable, which is composed of 240 Nb_3Sn strands and 120 copper strands, is assumed to have a basic distribution of strands on the bonding surface as shown in Fig. 2. The radius of each strand is 0.39 mm [5]. The contact pattern of the strands on the bonding surface is determined by superposing the distributions of the strands of the two terminals.

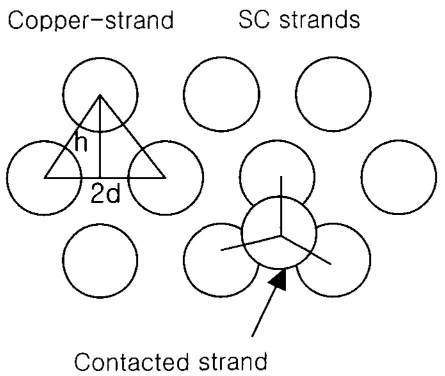


Fig. 2. Assumed basic distribution pattern of the strands in the cable.

In order to anticipate the DC resistance and the bonding strength of the joint, the contact area of the strands on the bonding surface is first calculated. The cable filling factor *Fi*, the fraction of the cable filling space bounded by the interior wall of a terminal, can be expressed as a function of d that is a half distance between the centers of the neighboring strands when the strands are distributed as shown in Fig. 2. The half distance d between the neighboring strands can be expressed as a function of cable filling factor as follows;

$$F_i = (r/d)^2 \pi / (2\sqrt{3}) \tag{1}$$

$$h = d\sqrt{3} \tag{2}$$

$$d = \frac{r}{\sqrt{F_i}}\sqrt{\frac{\pi}{2\sqrt{3}}} \tag{3}$$

where r is the radius of the strand.

When a strand of a terminal is contacted with a strand of the other terminal, the contact area can be calculated with the following equation;

$$A = 2r^2 \cos^{-1}(s/2r) - sr(\cos^{-1}(s/2r)) \tag{4}$$

where s is the distance between the centers of the contacted strands.

The cable filling factor of a commercial CICC is about 0.65. Cable filling factor of 0.9 is calculated as a theoretical maximum value, which can be obtained without failures of the strands during cable compaction. In the range from 0.65 to 0.9 of cable filling factors, the mean contact area was calculated by changing the contact patterns of the strands. Many kinds of contact patterns are assumed by using random numbers. As shown in the Fig. 3, the contact pattern of the strands inside of the circle, which is the inside contour of the compacted cable, is determined by superposing two kinds of distributions. The other kind of distribution of strands in the joint is modified by moving and rotating the basic distribution of the strands. The arbitrary moving distance and rotating degree in each trial are chosen respectively by using random numbers.

Each contact area obtained from each contact pattern between the basic distribution of the strands and the modified distribution of the strands is calculated by Eq. 4. For each cable filling factor, 500 kinds of contact patterns are assumed to get a exact mean value. Fig. 4 shows a flow chart to calculate the mean contact area by using many kinds of contact patterns on the bonding surface. The FORTRAN program was created according to the flow chart of Fig. 4 [6].

The calculated mean contact area per strand increases almost linearly with an increase of cable filling factor as shown in Fig. 5. The standard deviation of contact area per strand is decrease with an increase of the cable filling factor.

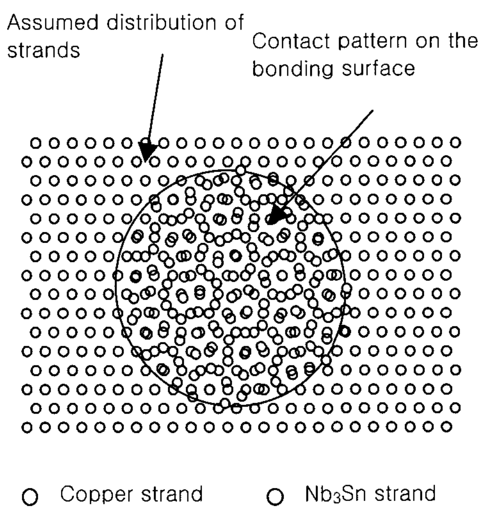


Fig. 3. Contact pattern of strands on the bonding surface.

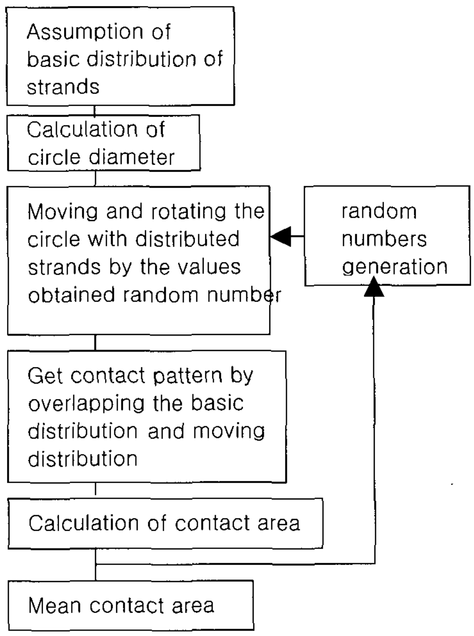


Fig. 4. Flow chart for calculating the mean contact area using many kinds of contact patterns on the bonding surface.

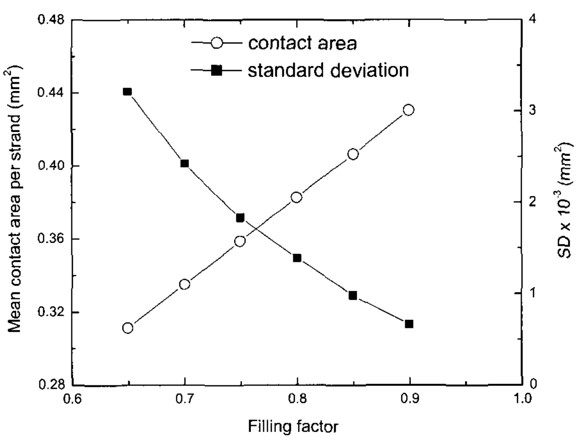


Fig. 5. Mean contact area per strand and its standard deviation change by increasing the cable filling factor in the butt joint.

This means that we can obtain a larger contact area with a higher quality when compacting the sleeve tightly. When the bonding strength is assumed to be proportional to the contact area, the bonding strength is also expected to increase almost linearly with an increase of cable filling factor.

3.2. Anticipation of the DC resistance

DC resistance may be changed by the contact patterns of the strands on the bonding surface. The current is assumed not to pass through the copper strands but to pass through just the superconducting strands across the inserted copper sheet. The contact patterns formed between the superconducting strands of the two terminals were considered for calculating DC resistance of joint. This contact pattern is different from the case of calculating the total contact area formed by both superconducting and copper strands. Because the thickness of the inserted copper sheet is much smaller than the strand diameter, the DC resistance between the bonded strands across the copper sheet can be calculated by the following formula;

$$k = \rho \frac{\lambda}{A} \qquad (5)$$

where k is the resistance between the bonded two strands, ρ the resistivity of the copper, ℓ the copper sheet thickness, and A the contact area. A superconducting strand can contact with the 0-4 superconducting strands of the other terminal. The current is assumed to pass just through the contacted area formed between the superconducting strands. The axial directional resistivity of the superconducting strand is almost zero, and the radial directional resistivity can be calculated by considering the ratio of copper and non-copper in the strand. The resistivity of copper, whose residual resistance ratio (RRR) is assumed as 50, is 3.4×10^{-7} Ohm-mm at an operating temperature [7]. Because of the chrome coating on the strands surfaces, the current flow between the neighboring strands in a cable is assumed as negligible. If the electrical contact resistance between the strands and the inserted copper sheet is not considered in this calculation, a voltage drop in the butt joint occurs by only the inserted copper sheet. With this assumption, the equivalent circuit of the joint can be depicted schematically as shown in Fig. 6.

From the equivalent circuit, the total current I can be expressed as in Eq. 6, and the DC resistance in the butt joint can be expressed as in Eq. 7 in the condition of the same voltage drop across the bonding surface;

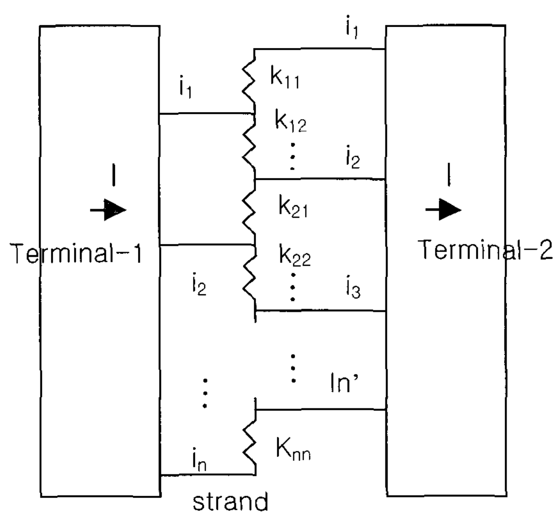


Fig. 6. Equivalent circuit of the butt joint.

$$I = i_1 + i_2 + \ldots\ldots + i_n = i_1' + i_2' + \ldots\ldots + i_n' \quad (6)$$

$$I = \Delta V\left(\frac{1}{k_{11}} + \frac{1}{k_{12}} + \ldots + \frac{1}{k_{21}} + \frac{1}{k_{22}} + \ldots + \frac{1}{k_{nn}}\right) = \Delta VR \quad (7)$$

where ΔV is the voltage drop, k_{ij} the resistance across copper sheet at the jth contact zone of the i th strand of a terminal, and R the DC resistance of the butt joint.

3.3. Calculation of DC resistance

On the bonding surface, the transport current is separated through the contact zones formed between the superconducting strands. The same procedure for obtaining the contact area on the bonding surface as shown in Fig. 4 was used to calculate the DC resistance of the joint by considering the just superconducting strands. The relation between the calculated DC resistance and the cable filling factor is shown in Fig. 7. The 200 different contact patterns were chosen by using random numbers for each cable filling factor. The DC resistance decreases with an increase of cable filling factor as shown in Fig. 7. The DC resistance of the compacted joint of cable filling factor of 0.9 is about 70 % of that of cable filling factor of 0.65. When the 240 superconducting strands are contact with 240 superconducting strands without a mismatch, a minimum DC resistance of about 0.3 n-ohm can be obtained analytically. This value is about 60 % that of the cable filling factor of 0.9.

The voltage drop distribution along a contacted strand including the inserted copper sheet was calculated by the commercial code to investigate the effect of the inserted copper sheet. The effect of the critical current of the superconductivity was not considered in this calculation. As shown in Fig. 8(a) and (b), most voltage drop occurs in the inserted copper sheet of 0.1 mm. When the inserted sheet is wide as in Fig. 8(a), the voltage drop is lower than that in the case of a small copper sheet as shown in Fig. 8(b).

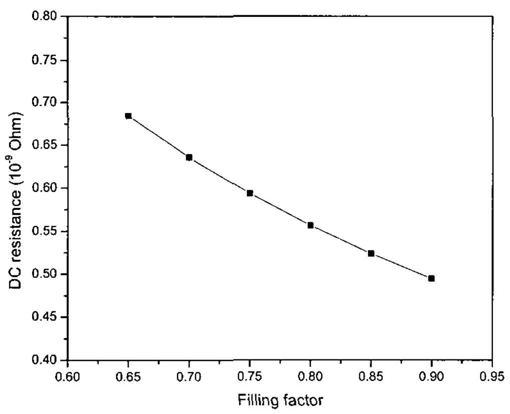
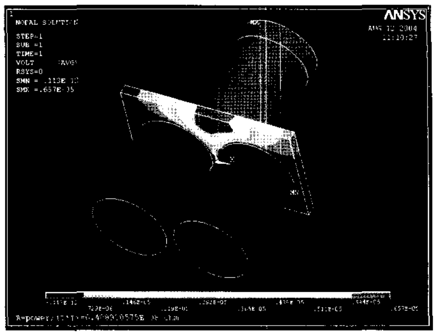
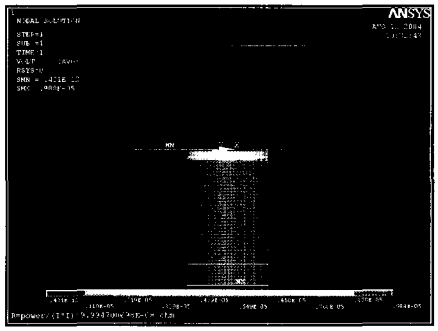


Fig. 7. Relation between the DC resistance and the cable filling factor.



(a)



(b)

Fig. 8. The calculation of the voltage drop across the inserted copper sheet depending on the area of inserted copper sheet. Case of (a) has wider copper sheet than case of (b).

The case of Fig. 8(b), copper sheet is laid on the cross section of a superconducting strand of the one terminal, is similar to the assumption used in the analytical calculation of DC resistance.

Since the effect of the critical current of the superconducting strands is not considered in this calculation, the current passing through the horizontal direction of a copper sheet can flow along the outside surface of the superconducting strands without a loss of superconductivity. This assumption is satisfied when the transport current is sufficiently low. It is expected that the low DC resistance of the joint may be measured at a low transport current, and the copper sheet may have a role of decreasing the DC resistance of the joint.

4. ANALYSIS OF THE ELECTRICAL CONTACT RESISTANCE

The DC resistance of the joint obtained during the CS model coil test in JAERI is about 3.2 n-Ohm at 46 kA and 2.6 T [4]. Because the joint of the CS model coil is composed of a two butt joint, the resistance of a butt joint is expected as about 1.6 n-Ohm. The CS model coil cable has a total of 720 superconducting strands and 360 copper strands. The estimated equivalent DC resistance for a 360 strands cable, which is used for calculation in this research, is about 4.8 n-Ohm. The calculated DC resistance of 0.49

n-Ohm at the cable filling factor of 0.9 as shown in Fig. 7 is much lower than that of the CS model coil.

Because the RRR of the copper sheet is almost the same in both cases, the difference of the DC resistance between the CS model coil and the calculated results may be expected to be caused by the electrical contact resistance between the copper sheet and the cable strands. The calculated electrical contact resistivity per the two layer of the top and bottom of the copper sheet, is about 2.97 x 10^{-7} Ohm-mm^2/two-layer when comparing the calculated DC resistance with the result of the CS model coil using the FORTRAN program as shown in Fig. 4. Considering the calculated electrical contact resistance, the relation between the DC resistance of the butt joint and the cable filling factor is obtained as shown in Fig. 9.

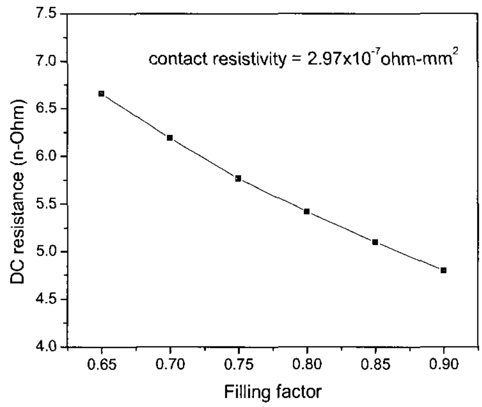


Fig. 9. The relation between the calculated DC resistance of the butt joint and cable filling factor considering electrical contact resistance.

5. CONCLUSION

Random numbers were used to simulate many kinds of contact patterns of the strands on the bonding surface for calculating the contact area and the DC resistance of the butt joint analytically. The calculated DC resistance decreased with increase of cable filling factor. The bonding strength is expected to increase lineally with an increase of cable filling factor when considering the variation of the contact area. The DC resistance at the cable filling factor of 0.9 is about 0.48 n-Ohm, which is about one-tenth of that in the CS model coil test, when not considering the electrical contact resistance. The calculated electrical contact resistivity between strands and copper sheet is about 2.97 x 10^{-7} Ohm-mm^2/two-layer when comparing the calculated DC resistance with that of the CS model coil.

ACKNOWLEDGMENT

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