Abstract. We achieved a very low resistance at 0.02 ~ 0.03 μΩ (12 nΩ cm²) across the non-superconducting joint with an area of 2 x 20 mm² for YBCO coated conductors produced by pulsed laser deposition (PLD). The joint technique was very simple in which YBCO coated conductors were stuck in a face to face manner with Ag surfaces in contact and heat-treated at 500°C in an oxygen atmosphere. We also confirmed that the good superconducting properties of the YBCO coated conductors were maintained after completion of the series of joint procedures. Furthermore, a low contact resistance of 0.5 nΩ cm² at the interface between the YBCO film and the Ag stabilizing layer was confirmed.

1. Introduction
Joint processing for two individual YBCO coated conductors is one of the most indispensable techniques for practical applications. There are two types of joint technique for superconductors. One is a superconducting joint and the other is a non-superconducting joint using a low melting point metal such as a soldering material. The key factor of a non-superconducting joint by welding and/or soldering techniques is to realize a low contact resistance without degrading the superconducting properties. Although the joint technique is a very critical issue for real applications, only a few studies have been reported to date, and all of them are about joints using soldering material.

In the case of a joint using a soldering material, resistance across the joint must become high because it includes resistance of Ag, a soldering material and contact resistance of interfaces between a soldering material, Ag stabilizing layer and YBCO. On the other hand, diffusion joining using Ag stabilizing layers is expected to reduce resistance across the joint without resistance of a soldering material and contact resistance. In this paper, we studied the diffusion joint process in which an Ag surface is put over the other immediately in a face to face manner.

2. Experiments
The YBCO coated conductor produced by pulsed laser deposition (PLD-YBCO), which was stacked Ag, YBCO, CeO2, and Gd,Zr,O4 (GZO) in the thickness of 13.0, 2.0, 1.2 and 0.8 μm respectively on the Hastelloy [4] was used for the joint experiment. It was cut into the size of 2 mm in width and 70 mm in length. Figure 1 shows the procedure for the joint experiment. The V-I properties were measured in liquid nitrogen before the joint process (fig.1 (a)). Next, the sample was cut at the center of the length (fig1 (b)). Ag surfaces of the divided samples were stuck together in a face to face manner with an overlapped area of 2 x 20 mm² (fig.1 (c)) without special cleaning of the Ag layer. The overlapped area was set in a holder made of Inconel as shown in fig.1 (d). It was held under pressure about 10 ~ 60 MPa at room temperature, which was controlled by torque on the screw of the holder. It was set in a tube furnace, and heated to 500 °C in pure oxygen gas at a flow rate of 300 ml/min, held for 1 h and cooled in the furnace to room temperature. The V-I properties across the joint after the heat treatment were measured (fig.1 (e)) in liquid nitrogen.

For the comparison with the diffusion joint of Ag, the PLD-YBCO coated conductor was joined using a soldering material. A soldering material (indium) was melted and spread in an area of 2 x 20 mm² on the Ag surface of the heated samples on a hot plate held at 250 °C, and then they were stuck together in a face to face manner. V-I properties across the joint were measured in liquid nitrogen.

We also measured contact resistance of the interface between the Ag stabilizing layer and YBCO. It is important to know it, because it is included in the resistance of the joint. The Ag stabilizing layer of the sample was partly etched in a solution of NH3:H2O2=1:1. The V-I property in liquid nitrogen was measured as shown in fig.2 before and after annealing from 500 °C to room temperature in an oxygen atmosphere.

Fig.1 Schematic illustration of the joint procedure and lead wire configuration for V-I measurement.

Fig.2 Schematic illustration of the configuration for V-I measurement of contact resistance of interface between Ag stabilizing layer and YBCO for the PLD-YBCO coated conductor.

3. Results

3.1. Contact resistance of the interface between Ag stabilizing layer and YBCO

The contact resistance between the Ag layer and YBCO was measured with the configuration shown in fig.2, before and after heat treatment from 500 °C to the room temperature in an oxygen...
atmosphere. The V-I properties of the sample before and after annealing were Ohmic. The contact resistance was estimated at 0.7 and 0.5 nΩcm² before and after annealing, respectively.

3.2. Properties of the diffusion and the soldering joint
The PLD-YBCO sample was joined using diffusion of an Ag stabilizing layer under a pressure between 10 and 60 MPa. Figure 3 (a) shows the V-I curves of the sample before and after the joint process in the overlapped area of 2 x 20 mm². The sample was joined under a pressure of 10 MPa during the heat treatment from 500°C to room temperature in an oxygen atmosphere. The V-I curves before and after joining were almost the same. It was made clear that the diffusion joint procedure maintained the good properties of the PLD-YBCO coated conductor. The voltage across the joint was less than 0.1 μV up to Ic of the sample, in spite of the small joint area of 2 x 20 mm². From the initial slope of the V-I curve, the resistance area product was estimated at 0.03 μΩ (12 nΩcm²).

For the comparison with the diffusion joint, the sample was joined using a soldering material, which has a low melting temperature. The V-I curves across the joint using indium and the as-cut sample in the size of 2 x 70 mm² are shown in fig.3 (b). The joint process retained the Ic value, but the resistance area product, 0.24 μΩ (96 nΩcm²), was about 8 times larger than that at diffusion joint.

3.3. Effect of the pressure during the joint procedure
We performed diffusion joining under various pressures. Figure 4 shows the joint pressure dependence of Ic/joint/Ic ratio and resistance across the joint in the overlapped area of 2 x 20 mm². Pressure was estimated from torque on the screw of the holder, and Ic/joint/Ic was the ratio of Ic before and after joining. Here Ic was decided by a criterion of 1 μV. It is clear in fig.4 that resistance was constant at 0.02 ~ 0.03 μΩ. However the Ic/joint/Ic ratio was reduced substantially above 30 MPa.

Fig.4 Ic and resistance across the joint as a function of pressure.
4. Conclusion
The PLD-YBCO coated conductor was joined by a very simple technique, which was diffusion joining using a Ag stabilizing layer stuck together in a face to face manner. A low resistance across the joint was achieved. The samples were compressed together and then heat-treated from 500 °C to room temperature in an oxygen atmosphere. The low resistance across the joint such as 0.02 ~ 0.03 μΩ (about 8~12 nΩcm²) was achieved with a joint area of 2 x 20 mm². Good superconducting properties were maintained after the joint procedure unless the pressure was too high. \( I_c \) was decreased when the pressure was higher than 30 MPa. Therefore the pressure during the joint processing should be carefully controlled. Furthermore we measured the contact resistance of the interface between the Ag stabilizing layer and YBCO. It was about 0.5 nΩcm² and was lower than the joint resistance and hence can be neglected in the analysis of the joint property.

Acknowledgement
This work was supported by the New Energy and Industrial Technology Development Organization (NEDO) as the Collaborative Research and Development of Fundamental Technologies for Superconductivity Applications.

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