# High Performance REBCO-HM Wire

## 1. INTRODUCTION

Beginning with the control of the global warming, various technologies have been developed all over the world to realize the carbon neutral society in the midst of a day to day growing concern over the carbon neutrality. Under the present circumstance mentioned above, the technology of the fusion is recently in the limelight and energetically developed by research institutions and venture companies in each country. Applying the technology of the fusion, it will be possible to realize a power generation technology which will never produce the carbon oxide emission or the long-lived radioactive waste which is inevitably produced in the nuclear power generation. In addition, it will continue to be a stable power source into the future, because resources needed for the fusion phenomenon exist richly in the sea. It is very important to control plasma to realize the very attractive fusion power generation mentioned above, because it is necessary to keep the plasma under the state of high density and high temperature for long time in a power generator. Such a fusion power generator has been developed and designed all over the world which controls the plasma based on the high magnetic field technology applied with superconducting magnets as a method to control the plasma. The superconducting wire becomes free from its electric resistance and a high power can flow in it when its temperature gets lower than a certain temperature (the critical temperature). An electromagnet which generates a high magnetic field can be realized with the use of the superconducting wire. Recently, a compact fusion reactor has attracted a wide attention, which is applied with REBCO wire, a kind of superconducting wires. The REBCO wire is the tape-shaped wire which has a superconducting layer made of a compound composed of rare-earth elements, barium (Ba), copper (Cu), and oxygen (O). The structure of our REBCO wire is shown in Figure 1. The black layer is the superconducting layer (REBCO layer). Even though its thickness is as thin as approximately 1.6 μm, a high current of over 100 A can flow in the wire which is only 4 mm wide under the liquid nitrogen temperature (approximately –196°C). We have continued the development of a higher performance REBCO wire through many years. The characteristics of our high performance REBCO-HM wire recently developed was approved by our customers and the wire was adopted in the superconducting magnet of the fusion reactor[1).]

Looking for other applications than the superconducting magnet of the fusion reactor, the development of a higher magnetic field by magnets is advancing in the application of analysis and research in the field of physics and chemistry and the demand for the high performance REBCO wire is growing. For example, when a magnet for Nuclear Magnetic Resonance (NMR) for an analytical instrument is operated under a higher magnetic field, the intensity of the detectable signal is increased and the resolution of analysis is remarkably improved, which will enable our more detailed analysis about materials. Our high-performance REBCO is also adopted in the instrument operated under the high magnetic field mentioned above.

## 2. DESIGN OF HIGH PERFORMANCE REBCO-HM WIRE

The high current performance under the magnetic field environment is demanded for the REBCO wire, because either the superconducting magnet for the fusion reactor or that for producing the high magnetic field is operated

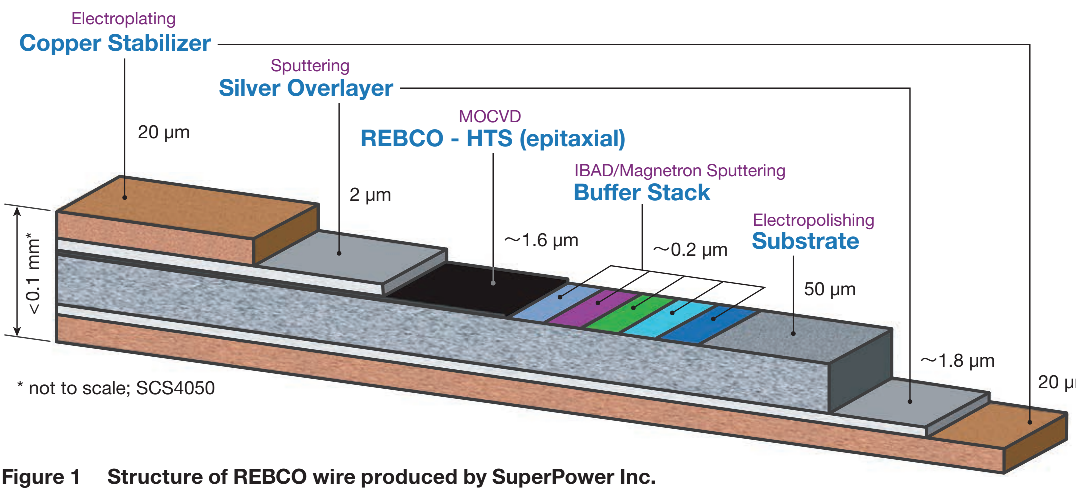


**Figure 1** Structure of REBCO wire produced by SuperPower Inc.

under the magnetic field environment. The movement of the magnetic field (flux quantum, technically speaking) which penetrates into the superconducting layer has to be blocked in order to maintain the high current performance under the magnetic field environment. When the magnetic field is moved, a voltage is generated producing the electric resistance and the high current performance cannot be maintained. When a part of the normal conductivity is formed in the superconducting layer, the magnetic field is trapped in the part of normal conductivity and its movement can be blocked. The part of the normal conductivity is called the artificial pinning center. The artificial pinning center of $BaZrO_3$ is created in our REBCO wire by adding Zr artificially. We implemented Zr at 7.5% of the material concentration ratio of our traditional REBCO wire. Under the higher magnetic field environment, more magnetic fields will penetrate into the superconducting layer. We have aimed at the higher density of the artificial pinning centers by improving the Zr concentration rate by doubling to 15% in order to control the movement of many penetrating magnetic fields efficiently. In addition, the composition ratio of our REBCO was optimized to create the artificial pinning center effectively.

## 3. CHARACTERISTICS OF HIGH PERFORMANCE REBCO-HM WIRE

Plan view Transmission Electron Microscopy (TEM) images of REBCO wire with Zr15% and REBCO wire with Zr7.5%, each of these REBCO composition ratio was already optimized are shown in Figure 2 and Figure 3. In Figure 4, a plan view TEM image of REBCO wire with Zr15% whose REBCO composition ratio was not optimized yet is shown. Parts looking like black circles are the artificial pinning centers of $BaZrO_3$. We can recognize that the thinnest artificial pinning centers of $BaZrO_3$ are formed in the highest density of the REBCO wire with Zr15% whose REBCO composition ratio was already optimized (see Table 1). In Figure 5 and Figure 6, the cross-section TEM images of the REBCO wire with Zr15% and the REBCO wire with Zr7.5% are shown. The $BaZrO_3$ pinning center is formed in a column shape perpendicular to the superconducting layer plane. The artificial pinning centers of $BaZrO_3$ look like thin grey columns in the vertical direction. We can recognize that the artificial pinning centers of $BaZrO_3$ are continuously linked together in a column shape all over the superconducting layer in the REBCO wire with Zr15%. By comparing, we confirmed that there were discontinuous parts in the areas surrounded by red broken line in the REBCO wire with Zr7.5% shown in Figure 6. It is when the size of the artificial pinning center is as large as that of the penetrating magnetic field that the artificial pinning center can catch the magnetic field efficiently. The size of the magnetic field penetrating into the superconducting layer is generally reported as to be several nm in radius (reported as 1.4 nm to 4 nm,[2), 3)]). It is estimated based on the

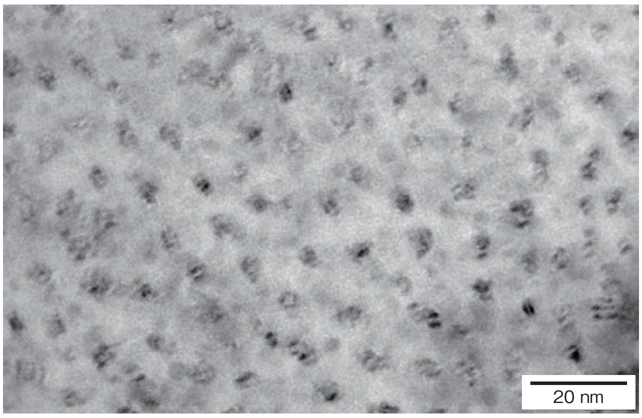


**Figure 2** Plan view TEM image of REBCO wire with Zr15% after composition optimization.

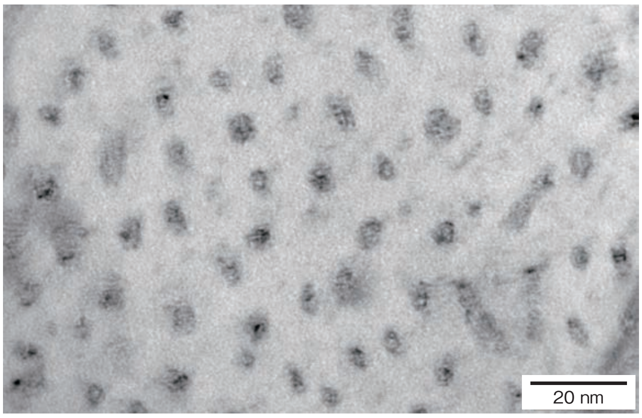


**Figure 3** Plan view TEM image of REBCO wire with Zr7.5% after composition optimization.

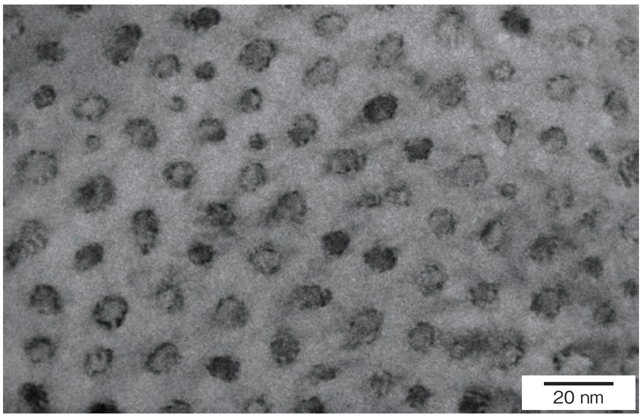


**Figure 4** Plan view TEM image of REBCO wire with Zr15% before composition optimization.

**Table 1** Pinning center configuration of each REBCO wire.

| Specifications of Wires | Pinning center diameter (average) (nm) | Pinning center density (average) (rods/cm$^2$) | Pinning center space (average) (nm) |
|---|---|---|---|
| REBCO wire with Zr15% (after optimizing the REBCO composition) | 3.3 | $7.5 \times 10^{11}$ | 7.6 |
| REBCO wire with Zr7.5% (after optimizing the REBCO composition) | 5.2 | $4.7 \times 10^{11}$ | 9.8 |
| REBCO wire with Zr15% (before optimizing the REBCO composition) | 5.4 | $4.2 \times 10^{11}$ | 12.3 |

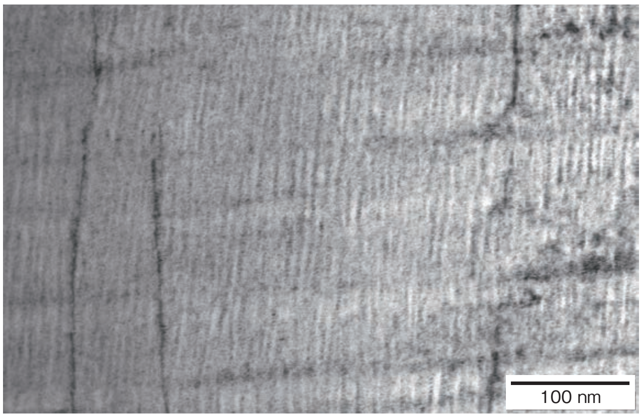


**Figure 5** **Cross-section TEM image of REBCO wire with Zr15% after composition optimization.**

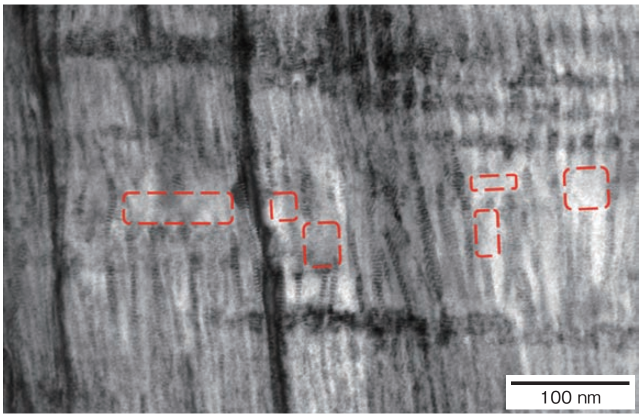


**Figure 6** **Cross-section TEM image of REBCO wire with Zr7.5% after composition optimization.**

shape and the structure of the pinning center which were confirmed by the TEM analysis that our developed REBCO wire with Zr15% can block the movement of the magnetic field even under the high magnetic field environment and has the required high current performance. In Figure 7, the measured results of the in-field current performance of wires with Zr7.5% addition and those with Zr15% addition in each magnetic field are shown when the magnetic field is applied perpendicular to the superconducting layer plane. $I_c$ on the vertical axis shows the maximum current value which can flow without breaking the superconducting state. We have confirmed that our developed REBCO wire with Zr15% had the current performance no lower than double of that of traditional REBCO wire with Zr7.5% in the temperature range from 4.2 K to 30 K (approximately from –270°C to –240°C) and under the high magnetic field of 10 T or higher.

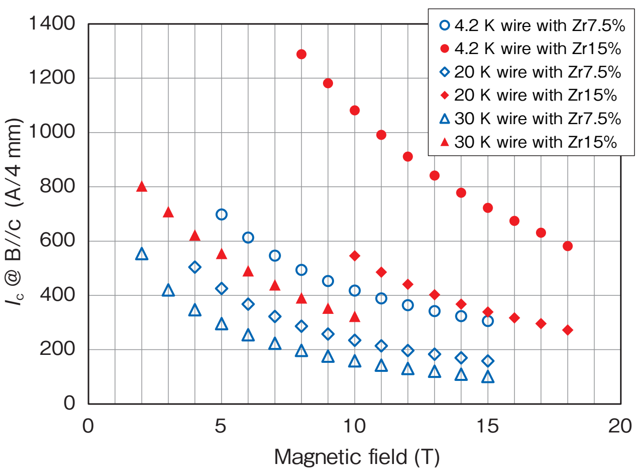


**Figure 7** **In-field performance of REBCO wire with Zr7.5% and Zr15%.**

## 4. CONCLUSION

We have developed our high performance REBCO-HM wire for the superconducting magnet in the fusion reactor and for the superconducting magnet to produce the high magnetic field. Improving the concentration rate of Zr which is a material for the artificial pinning center and further optimizing the composition ratio of the REBCO, we have accomplished the higher density of the artificial pinning centers in comparison with the traditional REBCO wire to make tremendous improvement of the in-field performance. Our developed high performance REBCO-HM wire has satisfied the performance required by various customers and has been adopted for the superconducting magnet in the fusion reactor and for the superconducting magnet to produce the high magnetic field. We will drive our development further and supply our higher performance REBCO wires to support the social infrastructure with our high magnetic field technology.

### REFERENCES

1) Furukawa Electric HP > News Release > “Tokamak Energy and Furukawa Electric Group Strengthen Relationship to Progress Commercial Fusion Energy” By Tokamak Energy Ltd., Furukawa Electric Co., Ltd., and SuperPower Inc.
released on January 12, 2023 (Referred on February 20, 2024)
https://www.furukawa.co.jp/en/release/2023/kenkai_20230112.html
2) D.C.Larbalestier, A.Gurevich, D.M.Feldmann and A.Polyanskii: “High-Tc superconducting materials for electric power applications”, Nature 414 (2001), P. 368-377.
3) S.Nawaz, R.Arpaia, T.Bauch and F.Lombardi: “Approaching the theoretical depairing current in $YBa_2Cu_3O_{7-\delta}$”, Physica C 495 (2013), 33-38.

For more information, please contact:
Technical Service Section,
Superconducting Products Department,
Research and Development Division
TEL: +81-288-54-0504
Contact form:
https://inquiry-fec-form.spiral-site.com/enrd

Electronics Dept., Electronics & Automotive Div.,
FURUKAWA SANGYO KAISHA, LTD.
FAX: +81-3-5405-7615
E-Mail: MO_5403_54030207025100@furukawaelectric.com