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DEVELOPMENT OF HIGH PURITY NIOBIUM COMPONENTS AND CAVITIES FOR SRF ACCELERATOR

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Abstract

Comprehensive cavity fabrication process from Nb ingot was investigated. In order to purify ingots, 600 kW electron beam melting furnace was introduced in ULVAC. It makes possible the stable quality of Nb sheets and tubes. In evaluation of chemical components and residual resistivity ratio (RRR) of our materials, all the value satisfies the ASTM Type 5 (superconducting grade) specification. We performed the trial manufacturing of welding-type and seamless-type cavities were made of our high purity Nb ingots (RRR > 300). Accelerating gradient over 40 MV/m at 2K was obtained both cavities. Trial manufacturing for 3-cell seamless-type cavity as scale up study was also performed. We succeed in hydro-forming from seamless tube to 3-cell cavity shape.

INTRODUCTION

Nb materials used as SRF cavity must be highly pure because they are used in the superconducting state that is sensitive to impurities. The upper limit on the amount of impurities are specified in the ASTM standards as the high purity superconducting grade (ASTM Type 5) [1]. Nb is rather expensive among pure metals and there are still some challenges with technologies for mass-producing cavities at present, so technologies for manufacturing cavities at low cost with high productivity are strongly demanded.

We have taken a two-pronged approach to developing SRF cavities in order to solve the problems mentioned above.

The first is to establish a technology for refining high purity Nb ingots. The goal is to discover a technology for supplying Nb materials that provide the required purity and acceleration performance at the lowest price possible. A 600 kW electron beam melting furnace with high vacuum system has been introduced in the factory of ULVAC Tohoku, Inc. to develop methods for manufacturing such Nb ingots.

The second part of our approach is a manufacturing technique called the seamless method. In this method, Nb seamless tubes that are produced by an ULVAC original technology are directly formed into cavities. The aim is to establish a method to manufacture SRF cavities at a lower cost than those manufactured by the welding method that is mainly used at present. Some research has suggested that the seamless method in which no welding is required for the main bodies of accelerator cavities has cost advantages [2, 3]. We believe manufacturing costs need to be closely re-examined throughout all the actual processes from purifying raw materials to fabricating cavities, as we have been doing.

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MANUFACTURING HIGH PURITY NIOBIUM INGOTS

In order to manufacture high purity Nb ingots by electron beam purification, it is best to purify them at high power under high vacuum to effectively remove impurities, especially gases and high melting-point metals. ULVAC designed a 600 kW electron beam melting furnace with high vacuum system for manufacturing high purity Nb ingot. Figure 1 shows the appearance of the electron beam melting furnace.

In the International Linear Collider (ILC) project, the RRR required for Nb materials is more than 250 as specifications. Currently, high purity ingots that satisfy such a value can be produced using this melting furnace. Table 1 shows the chemical analysis results of an ingot with the RRR of 330 as a typical example of high purity. This shows that the ingot is high purity superconducting grade (ASTM Type 5).

Figure 1: 600 kW electron beam melting furnace [4].

Table 1: Impurity Element Analysis of Nb Ingot.

(ppm)

	H	O	N	C	Zr	Fe
ASTM Type5	5	40	30	30	100	50
ULVAC	1	<10	<10	10	<10	<10
	Si	W	Ni	Ti	Al	Ta
ASTM Type5	50	70	30	50	50	1000
ULVAC	<10	10	<10	<5	<10	140

PROTOTYPING SEAMLESS CAVITIES

Single-cell

In order to reduce the cost of manufacturing cavities, we have been working to use seamless tubes to cavity

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shaping by hydroforming, a method very different from the welding method. To manufacture a seamless tube from an ingot, the ingot is forged, a hole is bored, and then the tube is extended as shown in Figure 2. The tube material was spun to obtain a longer tube while using stronger plastic process. The outer diameter of the completed seamless tube for single-cell cavities was 130 mm, the inner diameter was 123 mm, the thickness was 3.5 mm, and the length was 400 mm.

The seamless tube was processed to form a cavity as shown in Figure 3. Both ends of the cell of the original tube (Figure 3 (a)) were pushed by spinning rollers in to the minimum diameter to form necks (Figure 3 (b)). The next process was hydroforming to expand the tube in two steps. The tube was heat treated for crystal recovery between the first step (Figure 3 (c)) and the second step (Figure 3 (d)).

The seamless tube was successfully formed into the cell shape through the processes mentioned above without rupturing. Both ends of the tube were cut off and beam tubes and flanges were welded on. The inside was given a mirror finish. Figure 4 shows the final shape of single cell seamless cavity.

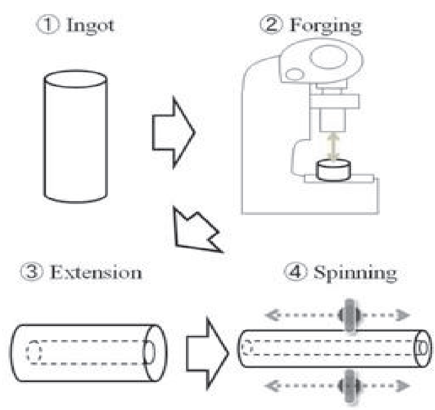

Figure 2: Manufacturing flow of seamless tube.

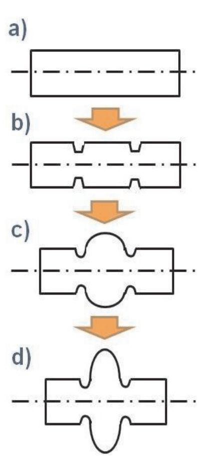

Figure 3: Schematic diagram of manufacturing process of seamless cavity. a) seamless elementary tube, b) after necking, c) after 50% hydrofoming, d) after final hydroforming.

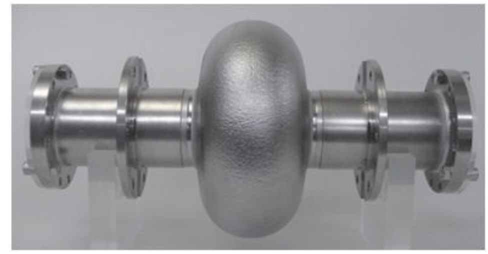

Figure 4: Single-cell seamless cavity [5].

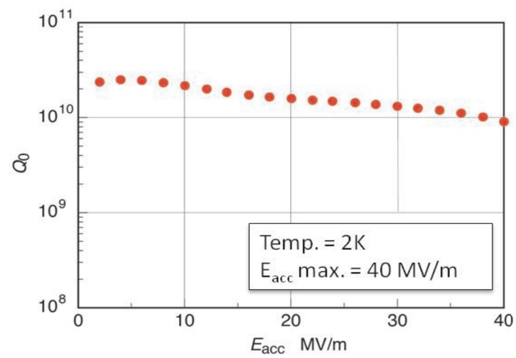

Figure 5: Accelerating performance for a seamless cavity.

The accelerating characteristics of this seamless cavity were also evaluated by vertical test at KEK. Q_0 was 1.3 × 10^{10} when E_{acc} was 30 MV/m and E_{acc}max. was 40 MV/m (Figure 5). These values are almost same as those of welding-type cavity in the case of good performance and satisfy the characteristics required for the ILC project (Q_0 > 1.0 × 10^{10} when E_{acc} is 31.5 MV/m and E_{acc}max. > 35 MV/m).

Three-cell

As explained above, we have succeeded in forming seamless single-cell cavity. However, a standard elliptical SRF cavity has mainly nine cells (nine-cell type). Therefore, we started prototyping seamless tubes to forming three-cell cavities as the scale up study.

A seamless tube was produced in the flow shown in Figure 2 as was the tube for single-cell cavities in the previous section. A seamless tube for three-cell cavities was prototyped through the processes mentioned above (Figure 6). The outer diameter was 138 mm, the inner diameter was 131 mm, the thickness was 3.5 mm, and the length was 830 mm. One difference with the seamless tube for single-cell cavities was that the diameter of the tube was increased by 8 mm. This was to reduce the amount of expansion needed to reach the final diameter from the original diameter in the hydroforming to avoid the risk of the tube rupturing in the process. Another difference was that the number of rollers in the spinning machine was increased from two to three. This modification made it possible to transmit the force from the rollers to the tube more evenly, which improved the processing dimension accuracy. The tube for single-cell cavities was

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machined to the target dimensions after the spinning process. The modification to the rollers made it easy to form cavities with dimensions within the target tolerances upon completion of the spinning process. Omission of the grinding process improved the yield of materials by 25%.

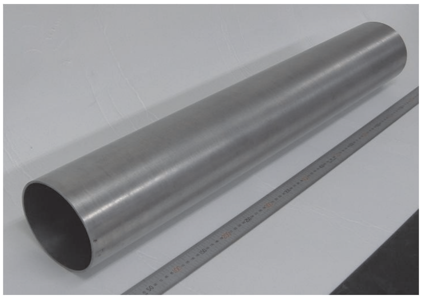

Figure 6: Nb seamless tube for three-cell cavity. (OD: 138 mm, ID: 131 mm, Length: 830 mm)

Evaluation results of a test piece cut from the seamless tube are explained below. First, the RRR was 350 and no decreasing was seen after it was processed. As for its mechanical characteristics, the tensile strength was 155 MPa and the elongation percentage was 53%. We know that these values compare favorably with those of existing high purity Nb materials for cavities. When tubes are formed with large deformation, controlling crystal structures is very important to reducing the risk of rupture. Crystal structures in the seamless tube for three-cell cavities were compared to those of the seamless tube for single-cell cavities described in the previous section by using the electron back scattering diffraction method (EBSD). Figure 7 shows the observation results. More smaller crystal grains are seen in the tube for three-cell cavities. The average crystal grain size in the tube for single-cell cavities is 121 μm. On the other hand, it is 89 μm for the tube for three-cell cavities. This is probably because stronger and more uniform processing was able to be applied to the material thanks to the modification to the spinning machine. Regarding the crystal orientations, the crystal grains for which the incline is within 15 degrees from (001), (101), or (111) are illustrated using the same color for each orientation. If aggregate structures exist, they are seen as a string of crystals of the same color. However, aggregate structures are not seen for both types, which show that the crystals are rather randomly oriented.

This seamless tube was processed the multi-step hydroforming as shown in Figure 3. Three parts of cell were formed simultaneously. We succeed to form into cell shape without rupturing (Figure 8).

SUMMARY

This paper explained the development of materials through a series of processes from purification of Nb ingots to prototyping of seamless cavities. A high-power electron beam melting furnace was introduced to manufacture ingots. ULVAC can obtain a high purity ingot that is required for general SRF cavity materials. Such high purity Nb ingots made by ULVAC were used to prototype single- and three-cell seamless cavities. We succeeded in direct forming from both seamless tubes to cavity shapes by using hydroforming. In single-cell seamless cavity, the maximum accelerating gradient attained to 40 MV/m. Our further work will aim to produce seamless nine-cell cavities and verify their cost advantages in comparison with the welding method.

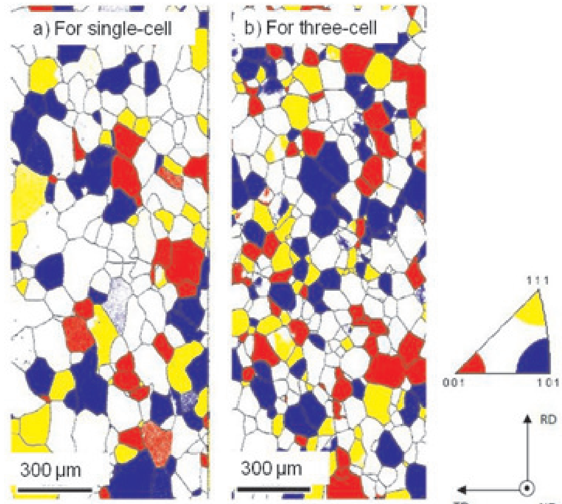

Figure 7: Crystalline orientation of seamless tube for a) single-cell cavity and b) three-cell cavity [5].

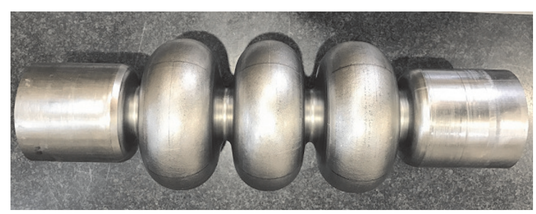

Figure 8: Three-cell seamless cavity.

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