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ADVANCED COPPER LINING FOR ACCELERATOR COMPONENTS

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Abstract

We have developed an electroformed copper lining having highly clean and smooth surface (i.e. little outgassing and high conductive copper) for use in accelerator components. The copper lining is produced by periodic current reversal electroforming with a low copper-content acid copper sulfate bath containing the specified amount of chloride ions (PR process). Deposit by PR process has the same value of IACS (International Annealed Copper Standard) as oxygen-free copper, and has higher breakdown field at first breakdown than the deposit by conventional types of electroformings. The cylindrical cavity with this new lining has been showed a low outgassing rate and an excellent Q value. The PR process is successfully applied to inner surface of DTL (Drift Tube Linac) and SDTL (separated DTL) cavities, surface of drift-tubes, and coils used for quadrupole magnets inside the drift-tubes.

1 INTRODUCTION

Oxygen-free copper is commonly used as a material of normal conducting accelerator components because of high purity, low outgassing and high breakdown field. Therefore, most of small cavities like electron linacs are made of Oxygen-free copper. Also, as the mechanical strength of the copper is sufficient for such small cavities, they consist of only the copper and they are simply made by cutting copper blocks. However, in case of proton linacs, the size of a cavity become so large as to causes insufficiency of mechanical strength. Therefore, proton linacs are firstly made from steel having higher mechanical strength than copper, and then the copper is lined to inner surface of the cavity. Electroforming is one of the lining methods commonly used for accelerator components. We have developed a pure copper lining by a new electroforming for JHF (Japan Hadron Facility) being constructed by KEK (High Energy Accelerator Research Organization).

2 THE LINING PROCESS

2.1 outline of copper electroforming

Copper electroforming can build up metal by electro chemical deposition of a relatively thick layer of metal over a base material. Electroforming is similar to electroplating. However, the differences between them is that the electroforming is used for forming a complicated structure and thickness of deposit is up to several millimeters, while the electroplating is used for covering and protecting the surface of metal and thickness of deposit is some micrometers. The one that is used for accelerator components is electroforming.

2.2 Conventional process

Copper formed by direct current has grains growing rough along with the deposit. Therefore, brightener (i.e. organic additive) is usually added to the bath to have smooth surface with thickness of several millimeters. However, brightener increases impurities of the deposit, and causes decrease of electrical conductivity. Also, it causes increase of outgassing from the deposit when heated to a high temperature or when electrical discharge happens. Moreover, the deposit is usually brittle and hard to be controlled for mechanical properties. Therefore, electroforming containing brightener cannot be applied to accelerator components like JHF DTL for which the proper strength, low outgassing and high electrical conductivity are required.

2.3 New process

Instead of electroforming using the bath containing brightener, we have developed a new copper electroforming. This new process (called PR process) is a copper electroforming by which thick and clean deposit is obtained by periodic reverse electrolysis. The deposit is obtained by periodically reversed current (for example, a cycle of 20 seconds normal and 4 seconds reverse) using a low copper-content acid copper sulfate bath containing no organic additives. The mechanical properties (i.e. elongation, tensile and yield strength) of the deposit can be controlled by adjusting chloride ion content and current density of the bath [1]. In addition, the deposits are so pure that the specimens are well electron beam welded forming smooth beads of a few porosities.

This PR process has been firstly applied to the combustion chamber of Japanese H-2 rocket's main engine, for the deposit produced by this process has proper strength and sufficient thermal stability. However, we have also focused on the property of its high electrical conductivity, and applied the PR process successfully to the accelerator components. Some examination results described below shows that the PR process is suitable for high-performance machines.

3 CHARACTERISTIC OF THE DEPOSIT PRODUCED BY PR PROCESS

3.1 Electrical conductivity

Electrical conductivity of electroformed specimens produced by pyrophosphate bath with brightener, acid sulfate bath with brightener, and acid sulfate bath without brightener respectively are compared to oxygen-free copper. Electrical conductivity is expressed as percent of the IACS (International Annealed Copper Standard). The %IACS is expressed as a percent of an annealed copper standard. Instrument which measure the voltage induced by eddy current in the specimen indicates the %IACS directly. Oxygen-free copper used for accelerator components actually have 102%IACS.

As can be seen from table 1, the %IACS of PR process is the same as that of Oxygen-free copper. Acid sulfate bath with brightener and pyrophosphate bath have considerably low %IACS than PR process.

Table 1: %IACS of electroformed copper specimens

Types of electroforming applied to specimens and reference material	IACS [%]
Acid sulfate bath without brightener (PR process)	101.9
Acid sulfate bath with brightener	76.8
Pyrophosphate bath with brightener	80.1
Annealed copper standard	100.7
Oxygen-free copper	102.0

3.2 Unloaded Q factor and outgassing rate

A cylindrical cavity having no drift-tubes or ports is fabricated with PR process to measure an electrical Q (quality factor) and an outgassing rate. The cavity has an inner diameter of 560 mm, and a length of 3321 mm, in which the lined copper of 0.5 mm thickness formed to inner surface of the cavity by PR process is included. Hollow forged steel is chosen for base material to prevent defect like ingot or blowhole which might occurs in the process. The lined copper is electropolished in order to obtain a smoother surface.

As a result, we obtained 78000 unloaded Q value at TM010 mode, which is 98% of the calculated Q. Also, there were no heavy molecule in the residual gas during the vacuum test and the outgassing rate in first exhaust reached $4*10^{-7}$ Pa/m^{-3}/sec/m^{2}. Therefore, prospects of reaching pressure of 10^{-5} Pa, which is required for the JHF linacs, is well obtained.

3.3 Electrical breakdown

Electrical breakdown fields of three kinds of electrodes produced by three types of electroforming respectively are measured [2]. The thickness of each electroformed copper is 0.5 mm. Breakdown field at first breakdown is shown in table 2. The breakdown field of PR process is approximately three times as high as other types of electroforming.

Table 2: First breakdown fields of electrodes

Types of electroforming applied to electrodes	First breakdown field [MV/m]
Acid sulfate bath without brightener (PR process)	40.8
Acid sulfate bath with brightener	13.4
Pyrophosphate bath with brightener	10.0

Moreover, the surfaces of the electrodes are analysed with XPS (X-ray Photoelectron Spectroscopy) before the breakdown test. As the result, the spectrum of copper was seen only from the PR process, but not from other two because their surface layers were covered with the hydrocarbon contamination and oxides. These results indicate that the conditioning time of an accelerator will be shorten when PR process is used.

4 APPLICATION TO ACCELERATOR COMPONENTS

The PR process has already been applied to JHF linacs and there are now under construction. The PR process is applied to inner surface of the DTL and SDTL cavities, surface of the drift-tubes, and the coil used for quadrupole magnets. Details of these components are described below.

4.1 Cavity

DTL cavity has an inner diameter of 560 mm and a length of 3300 mm. The cavity has rather complex shape to be electroformed. It has 7 large ports and franges which is for tuners and RF input couplers, and over 40 small ports which is for drift-tubes and post couplers. The cavity is made of forged steel while franges of ports are made of stainless steal. Defect free lining having a thickness of over 0.5 mm are required to inner surface of the cavity, inner surface of the ports, and grooves where o-rings and RF-contactors are putted in. The lining on the inner surface of the cavity is designed to have double layers, which makes the lining defect free by cutting off the growth of irregular copper deposits caused by shrinks or corrosion pittings inevitable for such a large forged steel substrate. At the end of the process, the surface is electropolished to obtain mirror-finished surface. As the electropolished surface is covered with oxide layer (which is much thinner than skin-depth), chromate treatment is not needed.

4.2 Drift-tube

Drift-tubes are hanged and placed at the center of the cavity by a stem having a diameter of 34 mm. Drift-tubes have an outer diameter of 140 mm. The bore-tube having a diameter of 13 mm is situated at the center of the drift-tube. The total number of drift-tube is 150 and each drift-tube has different length (53 mm to 165 mm). All of them are round shaped and mirror finished to prevent an electric discharge.

Drift-tube shells and stems are made of stainless steal. The copper having thickness of over 1 mm is lined all over the surface except the inner surface of the bore tube. Then, the surface is machined to proper size and finally, they are electropolished. Abrasive particles buried in the layer or denatured layer caused by machining is also removed when the surface is electropolished. The DTL cavity equipped with drift-tubes is shown in figure 1.

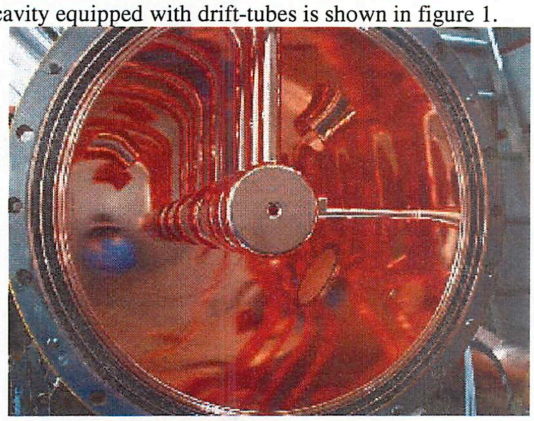

Figure 1: DTL cavity and drift-tubes.

4.3 Quadrupole magnet coil

A quadrupole electro magnet which needs an excite current of 1000 A is equipped inside the drift-tube. The diameter of the magnet is 115 mm. The hollow-conductor is normally used as a coil. However, in case of such a small and high current, hollow-conductor is not desirable because a thick hollow-conductor (needed for high current) enlarges the radius around the small magnetic pole and reduces the area of flux. Therefor, a new coil which has no radius (called "Sakae coil") has been developed. An outward appearance of the coil is shown in figure 2. The PR electroforming is applied to upper and lower surface of the coil as a lid of the groove. As the electroformed copper is brazed with a terminal, it must be thermally stable at brazing temperature, and thus the PR electroforming is applied.

The manufacturing process of the coil is described roughly as follow [3]. First, grooves and through holes is formed into a cylindrical oxygen-free copper block. Secondly, the grooves and through holes are filled with wax. Thirdly, the surface of the wax is coated with silver powder to give electrical conductivity. After that, the surface coated with silver powder is PR electroformed building up a lid of the grooves. Then, hollow structure is obtained when the wax is removed by heating. Finally, the holes in which magnetic poles are inserted are formed by cutting out unnecessary parts of the block, and then the coil is completed.

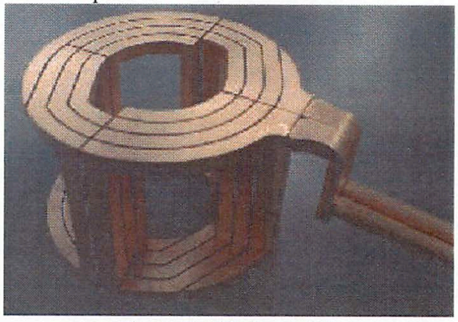

Figure 2: "Sakae coil".

5 CONCLUSION

The PR process, which firstly applied to fabricate complex copper structures, is also effective for forming the pure copper layer as oxygen-free copper. We focused on this point, and applied the PR process to accelerator components which is operated under high electric field and high vacuum conditions. The JHF linac is the first components to which the PR process is applied. The excellent properties of the deposit described above can be applied not only to the cavity of accelerators but also widely to the related components.

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