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Vacuum chamber made of soft magnetic material with high permeability

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ABSTRACT

In particle accelerators, a very effective way to shield an external magnetic field, which affects the beam inside the vacuum chambers, is to manufacture the vacuum chambers using soft magnetic materials with high permeability. We selected a permalloy and a ferritic stainless steel as candidates of those magnetic materials. However, until now the vacuum performance of vacuum chambers made of magnetic material does not yet have a proven track record.

Therefore we made a list of items to be examined and verified. These items are listed as follows.

1. General vacuum performance of the magnetic materials.
2. Magnetic annealing condition and its effect on each performance.
3. Magnetic and vacuum characteristic of a vacuum chamber made of soft magnetic material.

The outgassing rate of the magnetic materials was equivalent to that of an austenitic stainless steel. A good magnetic shielding performance is obtained by annealing at higher temperatures than 850 °C for both magnetic materials, although the performance declines, if the annealing temperature is too high. Furthermore the magnetic annealing in good vacuum is combined with vacuum heat treatment. The TDS spectrum showed that the reduction of hydrogen outflux from the bulk material near the surface was achieved by this process. Finally, we successfully produced a vacuum chamber with such a magnetic material, which will be used in a beam line at the 3 GeV J-PARC synchrotron, because satisfying magnetic shielding and vacuum performance were obtained.

1. Introduction

One of the reasons of beam loss in a high power accelerator can be unwanted stray magnetic field originating from magnets at a nearby beam line, which can distort the beam orbit so that the beam may partially hit a vacuum chamber wall. In such circumstances it is required to thoroughly shield the unwanted external magnetic field. The most effective way to shield such magnetic field is to cover the beam region by soft magnetic materials with high permeability. To minimize the amount of necessary shielding, this should be located as close to the beam region as possible. This naturally leads to the idea to manufacture the vacuum chambers using such soft magnetic materials. However, there is no proven track record for the magnetic materials from a vacuum performance point of view. This article shows the results of a vacuum performance examination combined with magnetic shielding performance, and the results of fabrication of a vacuum chamber (beam pipe) using those magnetic materials based on the measurements.

A part of the beam line in the 3 GeV synchrotron of J-PARC (Japan Proton Accelerator Research Complex) is one of the dedicated places, where the vacuum chambers made of soft magnetic material are installed. The objective of the vacuum and magnetic shielding is to achieve at least the current pressure of the standard beam pipe, and to shield the external magnetic flux density of about $2 \cdot 10^{-3}$ T.

From above aspects, first we will explain the selection of the magnetic materials. Second, the examination results for the vacuum and magnetic shielding performance are shown. Finally, the production and the performance of the vacuum chamber (beam pipe), which was made of the magnetic materials, are mentioned.

2. Soft magnetic materials with high permeability

Ferritic (Fe–Cr) stainless steel is one of candidates in many products containing magnetic materials because it is obtainable easily and it is reasonably priced. Its welding and machining properties are well known. Although the relative permeability μ_r ($=\mu/\mu_0$), where μ and μ_0 are the material permeability and the vacuum permeability, respectively, is not so high for example $\mu_r = 500$–1000, the target magnetic shielding performance can be

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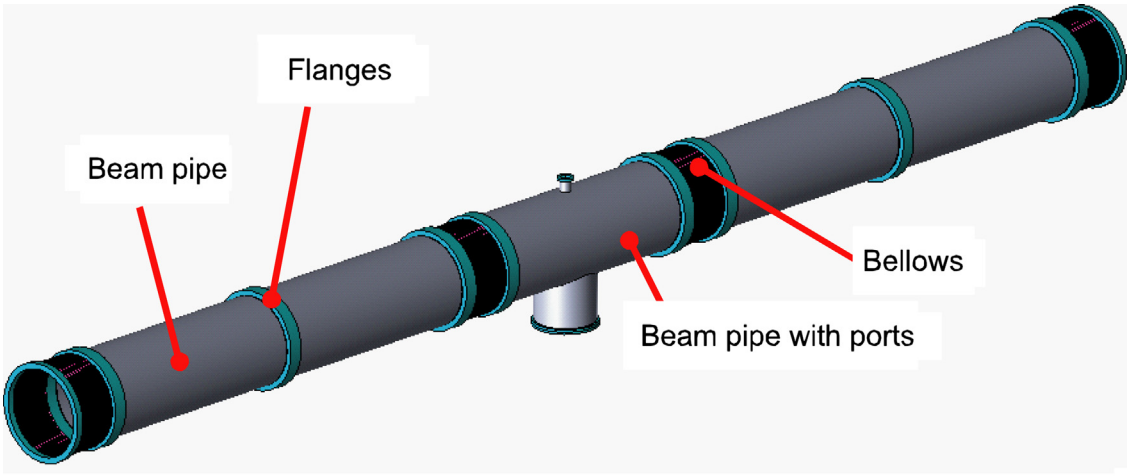
Table 1
Chemical composition of magnetic material (wt.%).

		Ni		Mo		Cu		Fe
Permalloy (permalloy PC)		77.6		4.6		3.6		BAL
	C	Si	Mn	P	S	Ni	Cr	Fe
Ferritic stainless steel (SUS430)	0.04	0.2	0.5	0.03	0.005	0.12	16	BAL

achieved when the thickness is more than 10 mm. Therefore we decided to use ferritic stainless steel for vacuum chamber flanges. The thickness of a vacuum chamber pipe is usually chosen in the range 2–4 mm to balance strength, bending workability, and welding properties. To achieve the target magnetic shielding performance for such thickness, we select permalloy (Ni–Fe–Mo), which has comparatively higher permeability. Common permalloy provides a relative permeability of more than 10,000. There are several kinds of ferritic stainless steel and permalloy described and listed in Japanese Industrial Standards (JIS) [1]. "Permalloy PC" and "SUS430" are the two candidates selected in our examination. Table 1 shows the chemical composition of the permalloy PC and SUS430 in mass percentage.

As mentioned in Section 1, to shield the unwanted external magnetic flux density from entering into J-PARC beam ducts is one of the objectives. In the target area, the magnetic flux caused by the magnets, which are located in the neighbourhood of the beam line actually causes the beam orbit distortion [2]. In order to roughly estimate whether the selected materials have enough magnetic shielding performance, a calculation was performed. Fig. 1 shows the calculation model. The 3D static magnetic field calculation was performed by the code JMAG Designer V10.5 [3]. The number of mesh points was about $1.3 \cdot 10^7$ in this model. In the calculation, the relative permeability μ_r of 700 was used for flanges, while μ_r of



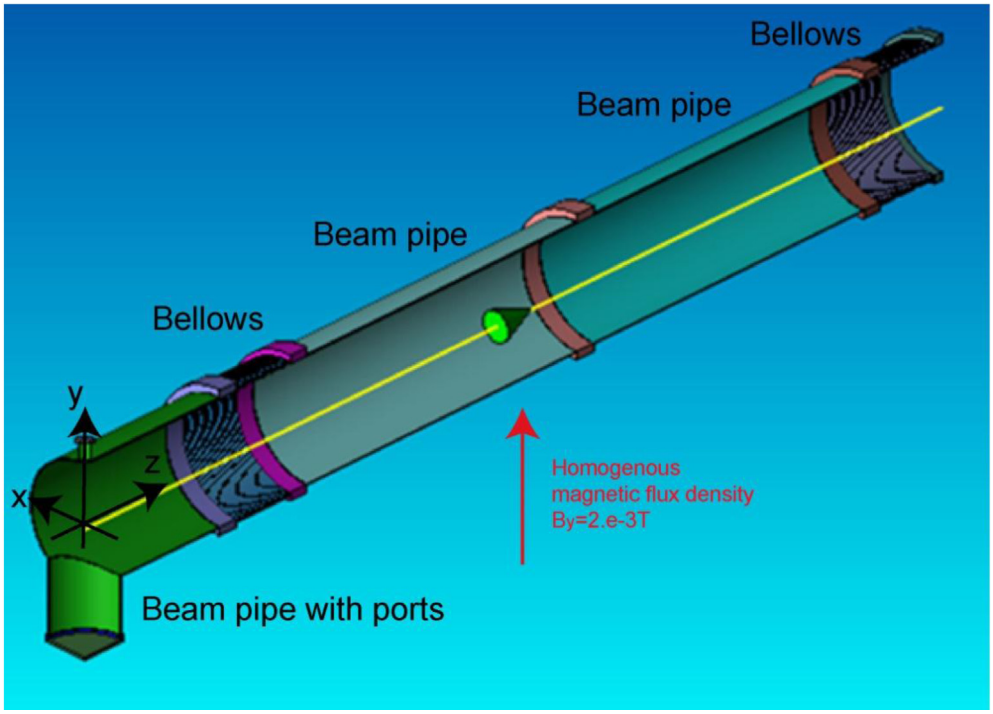


Fig. 1. The calculation model (full and 1/4 model) to estimate the magnetic shielding performance of the beam pipes and bellows made of soft magnetic materials. The model is based on the J-PARC 3 GeV synchrotron beam line, where we plan to install the magnetic material based beam pipes and bellows.