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Advanced Fusion Reactor Design using Remountable HT_c SC Magnet

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Abstract

A new concept of fusion reactor design is proposed using remountable high critical temperature (HTc) superconducting (SC) magnet. There are two advantages using this system. First one is that the magnet system can be composed by parts, which means it easy to replace the damaged magnet module. The second one is that it becomes possible to access the reactor first wall easily. In order to realize this system, we have performed experiments using HTc SC tape. The experimental results indicate that the resistance of the jointed region becomes about 60 μΩ, which shows the feasibility of this concept. Using this system the remoutable first wall system also has the feasibility based on thermomechanical analysis.

Keywords:

remountable HT_c superconducting magnet, butt joint, remountable first wall

1. Introduction

In order to obtain a public acceptance on fusion reactors as power plants, it is crucial to prove economic feasibility or at least to show its possibility with science and engineering development. As is well known, cost of fusion reactor designed now is still very expensive mainly due to construction fee including large SC magnet. Further the first wall of fusion reactor should be replaced periodically due to neutron damage or plasma disruption. In this paper, therefore, a new concept of fusion reactor design is proposed introducing remountable SC magnet and first wall, which can be only achieved by using HT_c SC magnet. Since the HT_c SC material can be operated at relatively high temperature, the specific heat of SC material, which is proportional to cubic of the temperature, becomes very larger at liquid nitrogen temperature. Due to this characteristic, some amount of heat generation, which is usually fatal in case of low critical temperature SC material, is allowable as far as the heat can be removed by coolant. It becomes, therefore, possible to joint the SC tapes directly using mechanical force, which enable us to design the remountable magnet. This magnet system will bring the extremely attractive advantages like drastic cost reduction of SC coils and accessibility to reactor components.

The first advantage is especially attractive in case of the helical reactor because the magnet system for helical reactor can be composed by combination of two kinds of small magnet module. This will bring drastic reduction of cost for the magnet system. Also it becomes easy to replace the magnet module damaged by, for example, neutron irradiation. Therefore, it becomes possible to treat the magnet system as a kind of consumer material.

The second advantage is also attractive because it becomes possible to access the reactor first wall easily.

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Since the magnet modules are directly connected by mechanical force, we can remove the magnet system to repair or replace the first wall as undergone in periodical inspection for fission power plants.

2. Remountalbe HT_c SC Magnet

Fundamental experiment for butt jointing method: Through our previous study [1], one of the most prospective jointing methods is to apply butt jointing methods for HT_c SC tape. The experimental results, however, showed relatively large electric resistance about 300 mW. Since this value is not small enough to design the remountable magnet from the viewpoint of heat generation, we perform other experiments, where the cross section of HT_c tape is conditioned by surface lapping. Figure 1 shows the experimental device used in this study. Ag-Mn alloy / Bi-Pb-Sr-Ca-Cu-O superconductor tape is used as a test piece. Silver ratio to the SC material is 2.7. The width and the thickness of this tape are 3.98 mm and 0.261 mm, respectively. Critical current density of this superconductor is 6.45×10^7 A/m^2 at 77 K, provided that SC state is defined as 10^{-13} Ωm. Compressive force acting on the cross section of tape is obtained by using difference of thermal expansion coefficient of the tape and vinyl chloride used as base foundation.

The experiment is carried out at 77 K for three cases (case 1, 2, and 3) of surface treating. In case 1 the tape is cut by nipper and then the cross section is ground by grinding paper (#1000). In cases 2 and 3, the tapes are fixed by plastic and then cut by diamond cutter. In case 2, water resist paper up to #2000 is used to make the surface flat, while in case 3, lapping file up to #8000 is used to obtain flatter surface.

Figure 2 shows microscope image of the tape cross section for cases 2 and 3. The black region is corresponding to HT_c SC material. By treating the surface with the #8000 lapping film, the surface is polished more flatly.

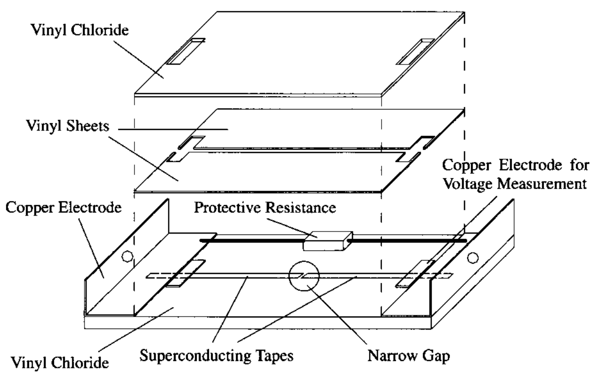
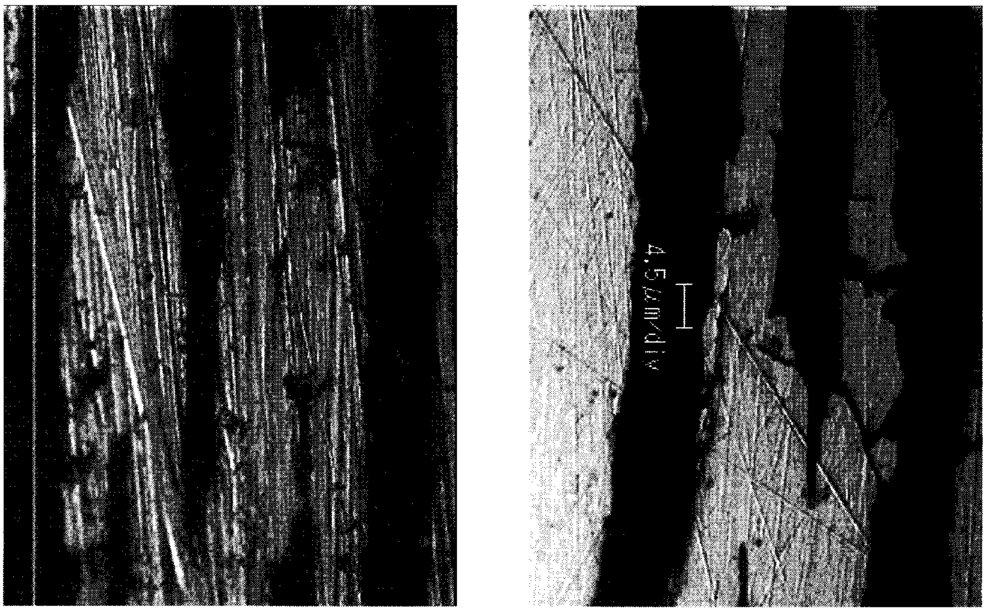


Fig. 1 Experimental apparatus



Case 2 (#2000)

Case 3 (#8000)

Fig. 2 Microscope image of cross section

Figure 3 shows the experimental results on the electric resistance when the strain of HT_c tape varies by changing the initial gap length between two tapes. The strain is evaluated by using thermal expansion coefficient of vinyl chloride and silver. The magnitude of transport current in determining the resistance is 60 A (about 90 % of the critical current). The value of resistance at 10 A, for example, becomes 90 % at 60 A, which may be caused by flux flow effect or difference of temperature rise due to joule heating. The result shows that the resistance decreases by increasing the strain and then reaches some limit value. This means that the tape bending occurs and that the stress acting on the tape does not increase over 0.2 % strain region. Around this region, the data for case 3 could not be obtained because the tapes were piled up after slipping. To improve the performance, the experimental system should be modified to suppress the bending of tapes.

For cases 1 and 2, we can reduce the resistance from the previous result of 300 μΩ to 60 μΩ. In case 3, however, the resistance is only reduced 260 μΩ even though the tape cross section is much flatter than those of cases 1 and 2 as approved from Fig. 2. There must be some reasons for this relatively large resistance. One reason can be that the compressive stress acting on the surfaces is not large because the contacting area becomes larger due to the flat surface. This is caused by the limitation of compressive force we can apply to the surface by this experimental system. Therefore there is large possibility to reduce the resistance by improving the experimental system. In the real magnet we can use the large electromagnetic force acting the SC cable by optimizing the geometry of cable cross section and the structure of casing.

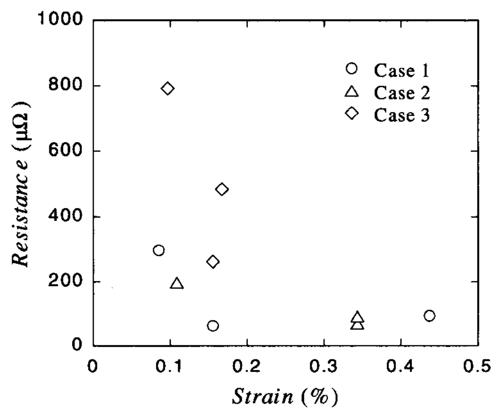
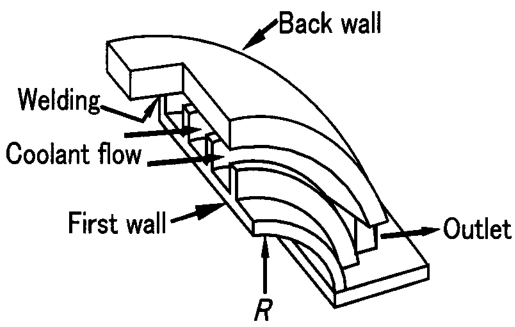


Fig. 3 Dependence of resistance on strain

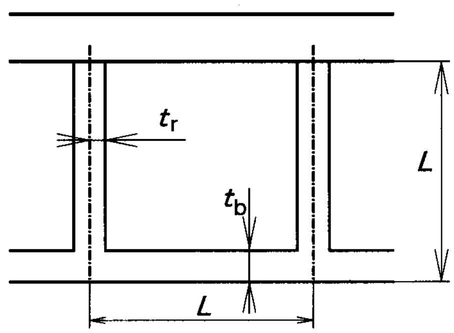
Outline of the magnet: In fabricating 1 T magnet of 5 m radius based on the present data, the total number of turns is calculated to be 1.2×10^5 using 67 A critical current (I_c) tape. Then the total resistance of magnet becomes 14 Ω, which will causes 63 kW heat generation. This value is still large and therefore the performance of butt jointing method should be improved one order more in terms of electrical resistance, whose goal is not far from the present results.

3. Remountable First Wall System

Concept of the remountalbe first wall: In the present design, the first wall should be replaced periodically due to neutron damage and plasma disruption. To avoid this replacement, many researches have been performed from both viewpoints of material development and reactor designing such as liquid first wall concept proposed by APEX program [2]. On the other hand, when the remoutable magnet system is successfully achieved, the remountable first wall concept can be acceptable, which enable us to replace the first wall as is done in fuel



(a) Concept



(b) Cross section of channel

Fig. 4 Remountable first wall

replacement of fission reactors. Figure 4(a) shows the concept of remountable first wall, which is divided into upper and lower parts. The end of each part is welded to the main structure, while the ribs are not welded. Therefore for maintenance or replacement, the magnet is removed at first and then the first wall is detached form the outer structure by solving the welded region. Finally the outer main structure is removed easily to access the fist wall.

Thermomechanical evaluation: Figure 4(b) shows the cross section of channel whose geometry is assumed to be a square. Flibe is chosen as coolant material to reduce the MHD pressure drop since the large inner pressure of coolant is not allowable in this design. The parameters used in thermomechanical evaluation are listed in Table 1. The first wall design is determined by considering maximum stress induced in the first wall, buckling pressure of arch and maximum temperature of the wall.

The maximum stress induced in the first wall is evaluated as a function of the thickness of first wall t_b and the span of channel L by considering thermal and mechanical stress. Figure 5 shows the result, where the coolant pressure is assumed 2 atm, which causes mechanical stress. When the t_b is smaller than 6 mm in case of 350 MPa, the mechanical stress is dominant and therefore by increasing the thickness, larger length L becomes acceptable. When the t_b becomes larger, the thermal stress increases and then the mechanical stress should be reduced by decreasing the length L. From the result, the allowable maximum thickness t_b in case of 350 MPa is evaluated about 6 mm. Since the maximum temperature in the first wall increases with using thicker wall, we choose 5 mm as the first wall thickness, where the maximum L becomes about 0.2 m for 350 MPa.

Figure 6 shows the critical pressure of buckling for shell structure evaluated by the following equation [3];

Table 1 List of parameters and material properties

q (heat flux)	0.6	(MW/m^2)
R	4	(m)
B	10	(T)
$E_{HT\text{-}9}$	180	(GPa)
$k_{HT\text{-}9}$	26	(W/m/K)
$\alpha_{HT\text{-}9}$	11.8×10^{-6}	(K^{-1})
ρ_{Flibe}	2020	(kg/m^3)
ν_{Flibe}	9.26×10^{-6}	(m^2/s)
k_{Flibe}	0.992	(W/m/K)
σ_{Flibe}	155	(S/m)

$$P_c = E\, I\, (k^2 - 1) / R^3 \tag{1}$$

where E, I, R and κ are Young's Modulus, moment of inertia of area, radius of curvature and a constant depending on the central angle ($\kappa = 2$ for π), respectively. In the figure, t_r corresponds to half of the lib thickness

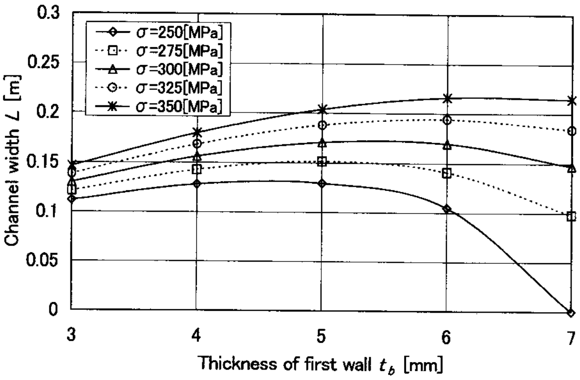


Fig. 5 Maximum stress induced in the first wall

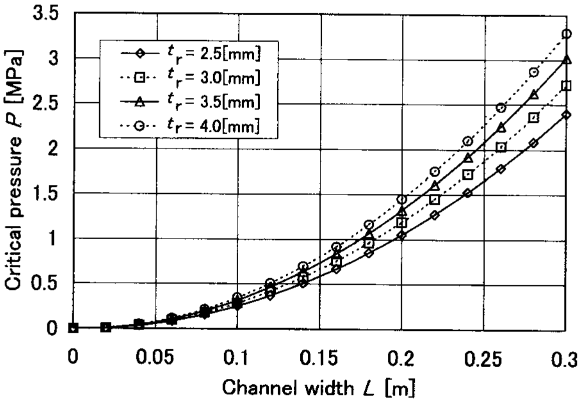


Fig. 6 Critical pressure for buckling

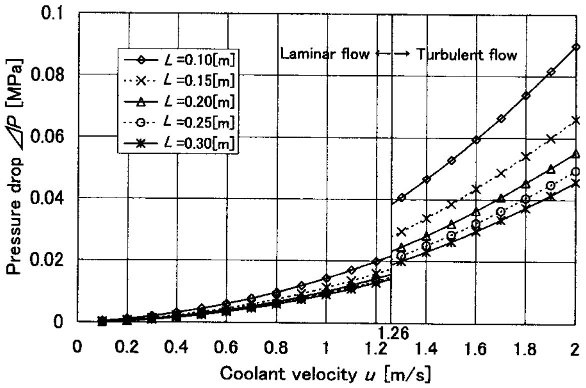


Fig. 7 Pressure drop in channel

as defined in Fig. 4(b). From the results the length L should be greater than 0.1 m because the coolant pressure is assumed to be 2 atm and the half thickness, t_r, does not affect the critical pressure so much. Finally by considering the structural integrity discussed in Fig. 5, we choose 0.2 m as the channel width and 2.5 mm as half of the rib thickness to make the wall thickness of channel become 5 mm.

In Fig. 7, pressure drop in the channel is plotted with the L as parameter. The pressure drop includes the pressure loss along the arch and 40 m straight pipe with 6 elbows using equations given by ref. [4]. The criterion for transition to turbulent flow is Re/Ha = 150 as given by ref. [4].

Since the coolant pressure is assumed 2 atm, which means the allowable pressure rise is 1 atm from the atmosphere, the allowable maximum velocity is evaluated 2 m/sec. Using this value the maximum first wall temperature becomes about 1080 K.

4. Conclusion

Through this study the following results are obtained.

1) By using the butt method for HT_c SC tape with surface treatment, the electric resistance is reduced to 60 $\mu\Omega$ at 90 % of the critical current I_c. By controlling the surface compressive stress, there is possibility to reduce the resistance more.
2) Based on the thermomechanical analysis, the remaoutable first wall also has possibility and one example design is demonstrated.
3) In this analysis, MHD effect is ignored. This effect should be considered in future work because the coolant channel proposed in this study is open one and therefore it is very easy to coat the channel surface by electrical insulator or to cut the electric circuit composed from the coolant and wall.
4) Through more experiments, the concept should be evaluated, which will bring breakthrough in the fusion reactor design.

Acknowledgement

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