Study on Quick Replacement of the Fusion Core Sections in Cassette Compact Toroid Reactor

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Abstract

Study of a conceptual design of "cassette" compact toroid reactor has been performed in focus on emphasizing the quick replacement handling. The core plasma, Spheromak, is ohmically heated in merging process between the core plasma and the gun produced Spheromak. The quick handling of replacement accomplished by using the functional material, SMA joint, is proposed in order to release from high neutron loading of the first wall for newly devised mechanical and structural method. The SMA joint can be used for connection or disconnection of the joint part by simple operation controlling the SMA temperature, without the extremely intelligent robot.

1. Introduction

In recent reactor designs, there is a trend toward the compact reactor that is smaller and cheaper than the other competitive energy source.[1,2] On the other hand, the potential of the compact toroid (CT) and the reversed field pinch (RFP) is recently growing up for the development of the fusion reactor with high power density. Compact reversed field pinch reactor with the power density of 15MW/m^3 has been analyzed by R.L.Hagenson and R.A.Krakowski, searching for the cost optimization in engineering considerations.[3] The spheromak plasma, one of compact toroids produced by the coaxial gun and the coils without linking the plasma, has been studied in the several laboratories in the United States and Japan.[4,5,6] Although compact toroid has still many physical problems to be studied including scaling dependence of energy confinement and the limitation on beta, the engineering approaches of compact toroid reactor operating at high wall loading will continue to be studied inevitably in future.

Given the present status mentioned above, the neutron wall loading is the most severe problem. In order to overcome this difficult problem, there will be two complementary approaches, the one for the long-termed development of fusion materials with resistance to the radiation damage on fusion material side, and the other for the development of the quick replacement technology to release from the damages, supported by newly devised mechanical and structural methods on system engineering side.

Study of a conceptual design of "cassette" compact toroid reactor has been performed in focus on emphasizing the quick replacement accomplished by using the shape memory alloy (SMA) coupling. This idea is applied here to the CT reactor for the first time, because the CT reactor is the easiest for applying this method, especially from the view point of remote handling of heavy weights with induced radiative emissions. This functional working of the

SMA joint is analyzed by the modified NIKE2D code.[7)]

2. Features of Cassette Compact Toroid Reactor (CCTR)

In this system proposed here, the fusion core with relatively high neutron wall loading should be replaced after about 6 months of operation, and each replacement has to be made as quickly as possible, for instance, about 10 days. Thermal output power is assumed to be 4000 MW of a conventional power plant.

The cross section of cassette compact toroid reactor is shown in Fig. 1. The core plasma, Spheromak, is produced by the magnetized coaxial gun(no.13) and ohmically heated by merging process[8,9)] of the intensive poloidal field and also alpha particles in DT fusion reaction. The fusion core plasma is built up in the plasma container(no.3) by the merging of ejected plasmas from the gun at the rate of 500 shots/s during 2 seconds. After burning, the flux is supplied at the rate of about from 9 to 10 shots/s ,where the magnetic energy per one shot is of about 1.1 MJ. The vertical magnetic field is applied by super conductor coil(no.12) in the vacuum field of 4.5 T at the plasma axis. The control coil(no.6) consisting of normal conductor is additively set near the first wall. At both ends of the plasma container, two diverter(no.1 and no.2) are equipped. In the steady state of CCTR, the radiation energy(1.1 MW/m^2) is directly transferred to the first wall at the rate of 30% of the total charged particle energy and the other charged particle energy(560 MW) is transferred to the diverters through the scrape off layer in 100 eV. The first wall(the plasma container) consists of the molybdenum tiles force fitted on SUS structural material and is cooled by light water in thin SUS pipe. The molybdenum tiles is of 2 cm and the SUS structural material is of 5 cm in thickness.

The joint between the diverter and the container, and also between the container and the coaxial gun consist of the functional SMA couplings(no.2) for the quick handling of replacement. The blanket(no.10) is separately placed from the first wall (the plasma container) in order to replace quickly and simply. The parameters of the compact toroid and the fusion power core are shown in Table 1.

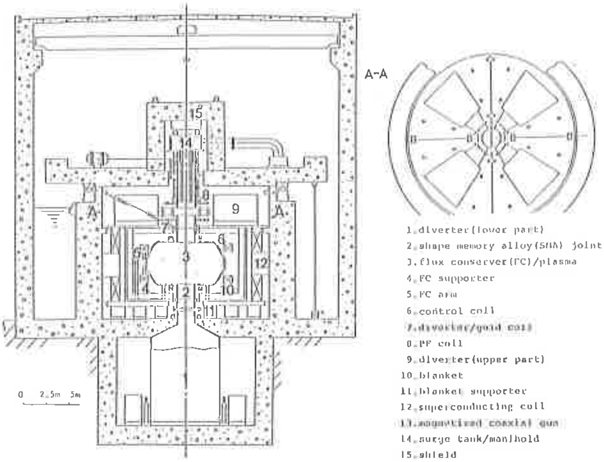


Fig.1 Cross section of Cassette Compact Toroid Reactor

Table 1 Plasma and FPC parameters

Plasma Physics/Engineering Parameters		
Major radius	2.25	m
Plasma radius	1.95	m
Magnetic axis	2.5	m
Plasma volume	188	m^3
Beta (axis)	0.24	
Average beta	0.3	
Toroidal current	43	MA
Poloidal current	76	MA
Average temperature	10	keV
Average density	5.6×10^{20}	m^{-3}
Alpha particle density	0.56×10^{20}	m^{-3}
Plasma pressure	17.8×10^5	N/m^2
Poloidal field B_p(max)	8.5	T
B_p(wall)	2.4	T
Toroidal field B_t(max)	5.5	T
Fusion power core parameters		
Gross thermal power	4000	MW
Net electrical power	1200	MW
Plasma container volume	244	m^3
First wall area	200	m^2
FPC volume	360	m^3
Neutron loading	16	MW/m^2

3.Quick Replacement of Reactor Core

Considering any fusion reactor, maintenance is one of critical issues independent of the level of compactness, and becomes the most important problem as proceeding with the realization of the schedules from the fusion test reactor to the commercial fusion reactor in future. There are mainly two approaches of maintenance.10) The first approach is that the coils especially, the super conducting coils are set as semipermanent structure and the first wall replacement is accomplished with the coils in place. The second one is that the first wall replacement is performed by the reactor core module as one unit including blanket, shield and coil systems, which are partially recycled.

In any case, hitherto, there is few repots for the actual maintenance technologies in the fusion reactor. Through the maintenance, the scheme of replacement of reactor core should be better to be quick and simple procedure. And the quick replacement technology is one of significant methods to release from the problem of high neutron wall loading. Here the quick replacement is accomplished by using the joints of the functional material, that is,the shape memory alloy (SMA).

3.1 Coupling system by using SMA joints

The SMA does not change its dimensional form by thermal contraction-expansion change, but by a phase change from a martensite crystal structure to an austenite crystal structure i.e. the inverse martensite transformation.11,12) The recovery forces are in approximate value of 450 MPa and make themselves to tight sealing hoop strength when used as a coupling.

The SMA joint was reported as a mechanical reliable coupler with performance superior to a socket weld by C.Sandberg and T.Klopack.13) This joint works in only one way process so that it is difficult to be disconnected after the joining is finished. However, by the special heat treatment like as remaining the residual stress or by changing chemical compositions of SMA the performances of the SMA joints are able to work in two way processes14) or all around memory behavior.15) These coupling performances are illustrated in Fig.2. In Fig.2(a) the all round memory coupling works like as expanding the diameter of joint by itself under the martensite transformation temperature. Under this temperature, the flanges can be inserted to the coupling. With raising the temperature of SMA over the austenite transformation point the coupling is shrunk to be connected between the faced flanges with vacuum tight. With decreasing the temperature below the martensite transformation point, the SMA coupler is reversibly expanded again to be able to release the flanges. This type coupler,however,cannot perform over the strain no more than 2% at maximum value, so that large tightening force cannot be obtained. On the other hand, the two way memory coupler is primarily expanded at the large strain more than 5% by the external force under the martensite transformation temperature. Over the austenite transformation temperature, the coupler is connected between the faced flanges with vacuum tight. Under the martensite transformation temperature, this coupler is expanded a little by itself but enough to be disconnected easily

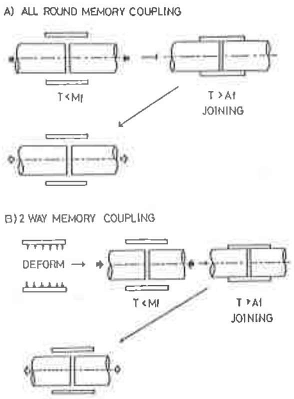


Fig.2 Illustrative explanations of SMA couplings

without friction as shown in Fig.2(b). In this design, the two way memory coupler with large tightening force is adopted for once service. There is no problem in fatigue of SMA because of once service.

Using these functional SMA coupling controlled only by SMA temperature, the replacement and maintenance can be operated rapidly and simply without the extremely intelligent robot system, keeping the safety.

3.2 Replacement process for reactor core parts

Process of disassembly of the reactor core parts is shown in Fig.3. At first, the upper diverters are disconnected from the co-axial gun body by controlling the temperature of the SMA coupler below the martensite transformation point. Then the diverters are removed. As repeating the same operation, the gun body is hung up and removed to the reservoir room. Next, the plasma container is also disconnected from the lower diverter and removed. Finally the SMA coupler is taken away after once service.

The details of the SMA couplers and the flanges are shown in Fig.4. The temperature control of SMA coupler is performed by water. The contact area between the SMA coupler and the flanges is very small so that the heat flow is choked enough to cool the SMA coupler.

To use this system is found to save the time for replacement and maintenance and also to save the working space in comparison with the conventional bolt maneuvering system.

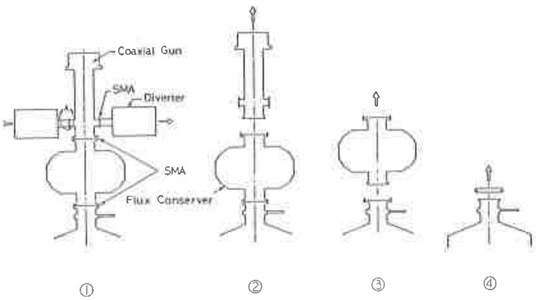


Fig.3 Disassembly of thr reactor core parts

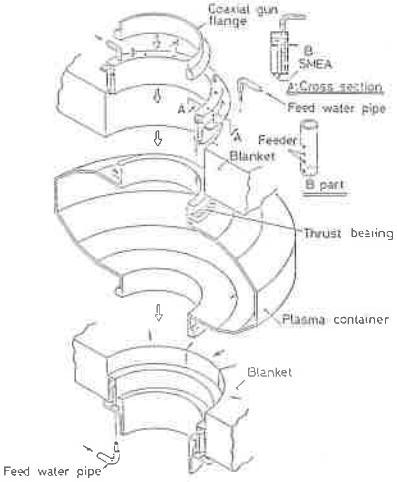


Fig.4 Details of SMA couplings and flanges

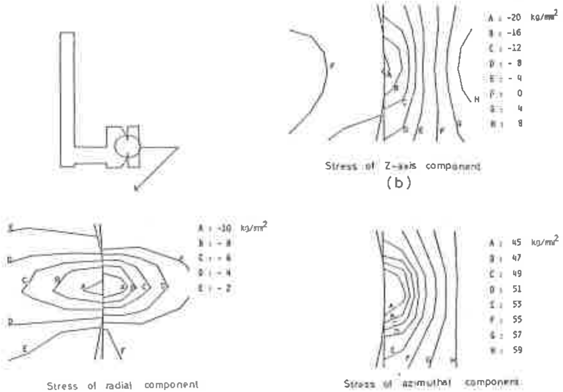
3.3 Tightening force of SMA coupling

The SMA coupling behavior was analyzed according to scheme from the preliminary calculation to the main calculation used the modified NIKE2D. By preliminary calculation, the parameter survey was carried out to calculate in the modified NIKE2D code. The NIKE2D code was developed by J.O.Halliquist[7)], where the large deformation can be treated and the coefficient of the thermal expansion can be also independently defined on each axis.

The functional material SMA is working by the endothermic and the exothermic phenomenon due to the latent heat. This latent heat can be introduced to the stress equation as follows.[16)]

$$\sigma_{ij} = l e_{ij}(T) - \beta_{ij}(T - T_o) + \frac{1}{2} C_{ijkl} C_{kl} \quad , (1)$$

where le_{ij}, β_{ij}, C_{ijkl} and T represent the latent heat per unit strain, the coefficient related by the thermal expansion, the coefficient related by the elasticity in tensor expression and the temperature of SMA, respectively. So the shape memory effect can be written by the equivalent coefficient of the thermal expansion due to transformation are shown in Table 2. The shape and dimension of the SMA joint are indicated in Fig 5. The diameter and the thickness of SUS flange are of 2 m and of 40mm respectively. The thickness of the SMA is of 30 mm. The results of the radial stress, the longitudinal stress, and the azimuthal stress distribution are shown in Fig.6(a), Fig.6(b) and Fig.6(c), respectively. The longitudinal distribution shows the bending mode toward the center axis, the radial one shows the compression mode and the azimuthal one shows the tension mode. The of the tightening pressure of this joint is calculated to achieve the pressure of about 15 kg/mm^2 at the peak value, as shown in Fig.7, whose value is equivalent pressure applied on the metallic O-ring of the vacuum seal. When the thickness of SMA joint is of 5 cm, the tightening pressure is represented by the dotted line in Fig.7. The peak value of the tightening pressure attained about 23 kg/mm^2, proportional to the thickness of the SMA joint.



Stress of Z-axis component
(b)

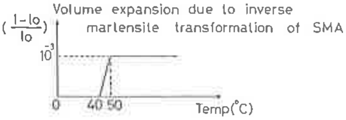
Stress of radial component
(a)

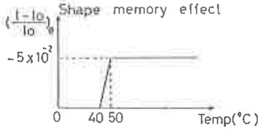
Stress of azimuthal component
(c)

Fig.6 Stress distributions

Table II Mechanical constants of SMA and SUS

	Temp °C	Young's modulus kg/mm^2	Yield stress kg/mm^2	Rate of work hardning kg/mm^2	Poisson's ratio	Coeficient of thermal expansion 1/°C
SMA	0	2880	10	28.8	0.15	10.0×10^{-6}
	40	2880	10	28.8		
	50	7200	60	72.0		
	100	7200	60	72.0		
SUS	——	20800	36	530	0.3	16.4×10^{-6}





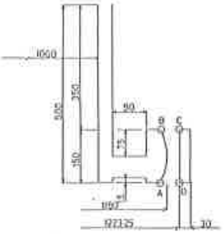


Fig.5 Shape and dimensions of sma joint

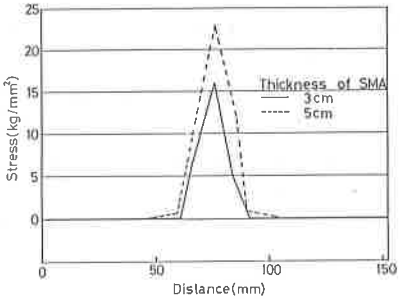


Fig.7 Tightening force between C and D of joint part in Fig.5

4. Discussion

There is few report on the effect of neutron irradiation on SMA behavior and are some reports on influence of electron irradiation. At the present time, it is difficult to obtain the informations for the radiation damage of SMA. The preliminary experiment of 14 MeV neutron irradiation has been performed in small fluence level ($2\times10^{15}/cm^2$) in Osaka University, but the effective results are not obtained yet. In CCTR, the SMA couplers are located at the outside of the SUS flanges of about 15 cm in thickness, far from the plasma core so that the couplers can be designed to be shielded in the relatively low radiation damage enough to keep the normal performance for 6 months.

To obtain a vacuum seal more tightly, it is considered that a thin layer of gold, aluminum or copper is lined at the contact part between SUS flange and SMA joint.

5. Summary

The quick handling of replacement accomplished by using the functional material, SMA joint is proposed in order to release from high neutron loading of the first wall for newly devised mechanical and structural method. The SMA joint enables the fusion reactor system to be more compact because the working space for the replacement and maintenance is not required due to simple operation for connection or disconnection of the joint part by controlling the SMA temperature, without the remote control bolt maneuvering by the extremely intelligent robot.

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