Potential of Copper Alloys using a Divertor Heat Sink in the Helical Reactor FFHR-d1 and their Brazing Properties with Tungsten Armor by using the Typical Candidate Filler Materials*)

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A tungsten block is supposed to be used as a divertor armor material on the helical reactor FFHR-d1. On the other hand, material selection of the heat sink and bonding technique between armor and heat sink are currently under investigation. On the material selection, copper alloy has a large advantage for the thermal conductivity, but its material properties such as toughness and thermal conductivity, are dramatically decreased due to the neutron irradiation. However, from the assessment of the neutronics environment on the divertor region of the FFHR-d1, copper alloys could be used for a heat sink especially at the outer divertor. In the ITER case, copper alloy (CuCrZr) pipes are joined by a brazing technique with Nicuman37 filler material. This combination has not been optimized for the FFHR-d1, because the toughness of the CuCrZr at high temperature over 450°C is dramatically decreased with increasing the temperature. As such, another candidate is an oxide dispersion-strengthened copper alloy (ODS-Cu) such as GlidCop®. For the bonding technique, a reliable brazing combination between "two kinds of copper alloys" and "three kinds of filler materials (MBF-20, BNi-6, Nicuman37)" were investigated from a viewpoint of mechanical strength. The most superior fracture strength among the three filler materials was BNi-6 with GlidCop®.

Keywords: copper alloy, tungsten, brazing, neutron irradiation

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1. Introduction

The divertor armor material of the helical reactor is considering tungsten block because tungsten has large advantages for low hydrogen isotope retention and low sputtering yield. However, material selection of the heat sink and bonding technique between armor and heat sink is currently under investigation. Under heavy neutron irradiation environment in a fusion reactor, reduced activation ferritic/martensitic steel (RAFM), such as F82H, is one of the candidate materials for the divertor heat sink or the cooling pipe [1], because it has high robustness against a neutron irradiation. However, F82H would not be able to withstand the heat load of the FFHR-d1 divertor over 10 MW/m^2, due to the high self-induced internal thermal stress, as discussed in Sec. 3.1.

Under such a condition, copper alloys with high thermal conductivity has a large advantage for the FFHR-d1 divertor. However, they cannot be acceptable under heavy neutron irradiation because the remarkable degradation of the material properties, such as toughness and thermal conductivity, occurs at a wide temperature range, as discussed in Sec. 3.2 [2]. However, from the assessment of the neutronics environment at the divertor of the FFHR-d1 to date, copper alloys could be used for a heat sink especially at the outer divertor of the torus [3].

In the ITER case, a precipitation hardened copper alloy (PH-Cu) of CuCrZr pipes are supposed to be used, and be joined by a brazing technique with Nicuman37 (Cu52.5%, Mn38%, Ni9.5%) filler material to the tungsten armor [4]. This combination is not optimized for FFHR-d1 because the toughness of the CuCrZr at a high temperature over 450°C is dramatically decreased by increasing the temperature. The operation temperature of the divertor heat sink in the FFHR-d1 is currently under discussion, but is hoped to be use at a high temperature range over 100°C to obtain a good efficiency of the energy conversion. Under such a situation, an oxide dispersion-strengthened copper alloy (ODS-Cu) such as GlidCop® (Cu-0.3wt%Al_2O_3) is another candidate copper alloy. If GlidCop® is selected for the FFHR-d1, the filler material of Nicuman37 might not be able to be used for maintaining a reliable brazing condition during an entire operation period.

In this paper, we first discuss the advantage of the copper alloys against the thermal heat loading compared with the F82H. We then briefly review mechanical properties of

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the two copper alloys CuCrZr and GlidCop® in high temperature range. Then, degradation of the material properties under neutron irradiation is reviewed and discussed. Next, reliable brazing combinations between "two kinds of copper alloys" and "three kinds of filler materials" are discussed based on the results of the brazing test of copper alloys to tungsten. Finally, the best combination of the copper alloys and brazing filler materials are summarized from these results and discussions.

2. Structural Advantage of FFHR-d1 Divertor

The intrinsic structure of the FFHR-d1 is similar to the Large Helical Device (LHD) [5]. While device size is four times larger than the LHD, the major radius (R) is R = 15.6 m [6–8]. In the case of the heliotron type devices, the edge magnetic structure is more complicated than the tokamak devices, and an intrinsic divertor exists without additional coils [9]. Because of such characteristics, the total length of the divertor trace (L_{div}) of the FFHR-d1 is L_{div} ~ 900 m which is much longer than that of the same sized tokamak reactors, i.e., Slim-CS (R = 5.5) [10]. Consequently, the total area of the divertor strike point of the FFHR-d1 can be estimated to be ~32 m^2. These characteristic have a large advantage for distribution of the divertor heat flux.

The main fusion reaction is supposed to be the following equation.

$$\mathrm{D + T = {}^4He\ (3.52\,MeV) + n\ (14.06\,MeV)}.$$

If we assume the 33% of the power conversion efficiency for acquisition of a 1 GW fusion power gain, the total fusion power output of the FFHR-d1 is required to be ~3 GW [6]. The α heating ratio can be estimated to be 3 GW × 3.5/(14+3.5) ≈ 600 MW. If we assume that the radiation loss is ~100 MW, the remaining α heating power of 500 MW is absorbed by the divertor, an average heat flux is reached around 15.6 MW/m^2. If the radiation loss is assumed to be 35% of the total α heating power, average heat flux is decreased to around 10 MW/m^2. However, since the heat flux is not homogeneously distributed to the entire divertor strike point, the peaking heat flux could exceed 10 MW/m^2.

3. Potential of the Candidate Copper Alloys for FFHR-d1

3.1 Advantage of the copper alloy against the thermal heat loading

The advantage of the copper alloys against the thermal heat loading is compared with F82H. Figure 1 (a) shows the temperature gradient between surface and back surface of a pure copper (Pure-Cu) and F82H as a function of an input power. Input power from the divertor plasma in the FFHR-d1 is expected to exceed 10 MW/m^2. In the

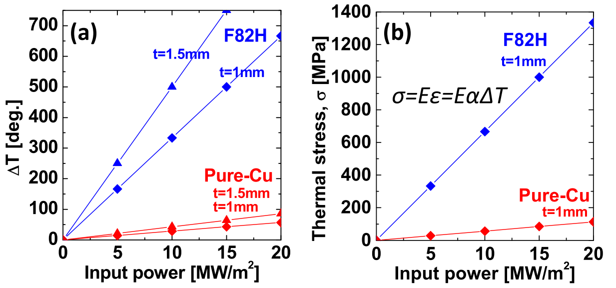

Fig. 1 (a) Temperature gradient as a function of an input power in different thickness of F82H (30 W/m·K) and Pure-Cu (320 W/m·K). (b) Induced internal thermal stress (σ) as a function of an input power in the 1 mm thickness of F82H and Pure-Cu. E: Young's modulus [Pa], α: Thermal expansion coefficient [K^{-1}].

case of Pure-Cu, temperature gradient (ΔT) is below 50°C with a thickness of 1~1.5 mm. In the case of F82H, ΔT is over 300°C and 500°C with a thickness of 1.0 mm and 1.5 mm, respectively. Figure 1 (b) shows the induced internal thermal stress (σ) in the Pure-Cu and F82H as a function of an input power calculated by a simple equation which is shown in Fig. 1 (b), the ΔT was derived from Fig. 1 (a). This calculation is a very rough estimation, and took into account only the internal (whole) stress produced by its own thermal expansion on a fully restricted condition. High thermal stress of ~600 MPa is induced at ~10 MW/m^2 in the 1 mm thickness of the F82H. Since the yield strength of the F82H is ~500 MPa, this material cannot be used in this condition. On the other hand, internal thermal stress of Pure-Cu is ~100 MPa even at ~20 MW/m^2. This result indicates that copper and their alloys can be sufficiently used under ~10 MW/m^2 heat loading and have a large advantage for handling the high heat loading in the divertor.

3.2 Degradation of the material properties under neutron irradiation

As mentioned in section 1, the developed and assessed copper alloys for fusion use to date are mainly categorized as an ODS-Cu such as GlidCop® and a PH-Cu of CuCrZr. We assessed these two alloys in this study. The GlidCop® is an Al_2O_3 dispersed copper, and it has superior high temperature strength over 300 MPa even after the annealing up to about 1000°C. However, since its manufacturing process is complicated through the special powder metallurgy (PM) processes, its cost is rather high. On the other hand, the manufacturing process of the CuCrZr has an advantage because it can be used as a casting. The thermal conductivity of both the GlidCop® and CuCrZr are almost the same as the Pure-Cu.

Determining the radiation threshold for using the copper alloy under neutron irradiation is difficult because not only energy spectrum and dose of the neutron but also material temperature are complicatedly related to changing

Table 1 Typical threshold parameter of the GlidCop® and CuCrZr related with the radiation-induced hardening/softening [2, 11]. The same parameters of Pure-Cu are also listed together for comparison.

Pure- Cu and Cu alloys	Yield strength at room temperature	Threshold temp. of radiation induced hardening/softening	Radiation limit for radiation induced hardening	Radiation limit for radiation induced softening
Pure-Cu	~60 MPa	---	~0.1 dpa	---
GlidCop® (ODS-Cu)	> 400 MPa	~300˚C	~0.2 dpa (below 300˚C)	1~2 dpa (slowly)
CuCrZr (PH-Cu)	> 400 MPa	~280˚C	~0.2 dpa (below 280˚C)	~1 dpa

the material properties. The changeable material properties by neutron irradiation are (1) radiation-induced hardening/softening [2, 11], (2) embrittlement by transmuted helium [12], (3) degradation of the thermal conductivity by transmutation products [2, 13], and (4) void swelling [2, 14–16]. These material properties directly affect the mechanical properties. From the earlier studies, it was clarified that the lowest radiation limit above four properties was "(1) radiation-induced hardening/softening" [2, 11–16]. Typical threshold parameter related with the radiation-induced hardening/softening was summarized in Table 1. The acceptable dose level of the radiation-induced hardening/softening in both copper alloys is 0.2∼1 dpa, and it has temperature dependence. Its threshold temperature of GlidCop® and CuCrZr are ∼300°C and ∼280°C, respectively. The hardening and softening occur below and above these temperatures, respectively.

This property directly affects the maintaining of the toughness of the heat sink materials. In the case of the ODS-Cu and PH-Cu, dispersed or precipitated particles into the matrix should act as an obstacle against the dislocation. However, in the case of the radiation-induced hardening, the saturated radiation-induced dislocation loops and stacking fault tetrahedras (SFTs) heterogeneously prevent a motion of the dislocations, and thereby the ability of the homogenous elongation is lost. Conversely, in the radiation-induced softening, particles precipitated or dispersed into the matrix are dissociated by neutron irradiation. Otherwise, original dislocations and voids are terminated due to the radiation induced recrystallization. Consequently, the obstacles for the movable dislocations disappear and thereby, materials are softened [11].

From the above information, the best material for the heat sink of the FFHR-d1 could be the GlidCop®, and its temperature should be kept at 300°C without any temperature frustration during operation period.

4. Brazing Test of Copper Alloys to Tungsten

4.1 Experimental procedures

The size of the copper alloys and tungsten for brazing tests are $30 \times 30 \times 38\,mm^3$ and $30 \times 30 \times 18\,mm^3$, respectively. Each $30 \times 30\,mm^2$ plane was used as a brazing surface. The selected copper alloys for this experiment are the CuCrZr and the GlidCop®. For the case of the GlidCop®, since the grains were elongated along the cold working direction, two kinds of block were extracted from the ingot. The first ones are the grain that were elongated perpendicular (⊥) to a brazing surface; the others were elongated parallel (//) to a brazing surface. The selected filler materials and their chemical compositions to be tested are summarized in Table 2. Brazing procedures were carried out in the high-vacuum furnace in the Metal Technology Co. Ltd. Since the temperatures of the solid and the liquid phases differ by each filler material, two types of heat treatment procedures were selected, as shown in Fig. 2.

Table 2 Chemical composition of the selected filler materials used in this study.

Filler materials	Solid phase temperature	Liquid phase temperature	Cr	Cu	Mn	Ni	P	Si	Fe	B
MBF-20	969˚C	1024˚C	7			bal.		4	3	3
BNi-6	875˚C	875˚C				bal.	11			
Nicuman37	880˚C	925˚C		52.5	38	9.5				

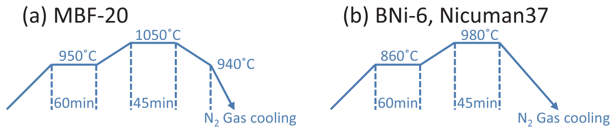

Fig. 2 Procedures of the heat treatment of (a) MBF-20 and (b) BNi-6 and Nicuman37 filler materials.

After the heat treatment procedures, the brazed blocks were fabricated to be the small size specimens with the size of $36 \times 5 \times 1.5\,mm^3$. Then, a three point bending test was carried out by using the SHIMADZU Autograph at Okayama University of Science.

4.2 Results and discussions

Figure 3 shows the stress-strain curves of the three point bending test for the nine combination patterns of the copper alloys and the filler materials. Since the five specimens were prepared for one combination, there are five stress-strain curves in one combination. In the case of the No. 2 and 4, specimens were not able to be fabricated as a small size specimens for the bending test because of the fracture of the tungsten just beneath the brazing. This might have been caused by any internal stress induced in the tungsten blocks due to differences of the thermal expansion coefficient between tungsten and copper alloys. While in the case of the No. 8, the brazing completely failed.

Therefore, the details of the discussions regarding the brazing strength have to be conducted using the remaining six specimens. In the case of MBF-20, fracture stress was quite low at around 50 MPa and 100 MPa for the CuCrZr and GlidCop®, respectively. This filler ma-

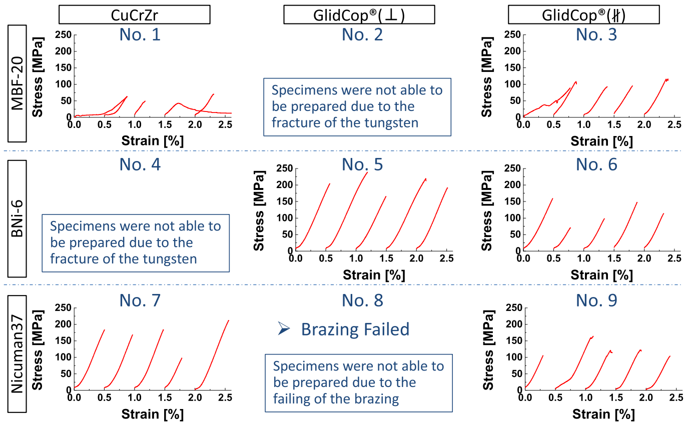

Fig. 3 Stress-strain curve of the three point bending test for the nine combination patterns of the copper alloys and the filler materials.

terial seems to be bad for the brazing. In the case of the Nicuman37, it has an interesting property. Although the fracture stress reached to ~200 MPa in the CuCrZr, it decreased to ~150 MPa, or the brazing failed completely in the GlidCop®. This seems to indicate that some chemical component, i.e., Cr in the CuCrZr might have acted as the effective intermediate object for the good brazing. Therefore, Nicuman37 will not be able to be used with GlidCop®. The most superior fracture strength among the three filler materials was BNi-6 with GlidCop® (⊥). The effects of the elongating direction, between perpendicular (⊥) and parallel (//) to a brazing surface against the brazing surface could not be identified in this experiment.

5. Summary

According to the current design of the FFHR-d1 and its divertor characteristics, the total area of the divertor strike point can be estimated to be ~32 m^2. This characteristic provides great advantages for distribution of the divertor heat flux. As such, the average heat flux is estimated to be around 10 MW/m^2.

The F82H cannot withstand under ~10 MW/m^2 heat loading because of its induced internal thermal stress. On the other hand, a copper and their alloys can be sufficiently used under the same heat loading.

From the assessment of the neutronics environment at the divertor of the FFHR-d1 to date, copper alloys could be used for a heat sink especially at the outer divertor [3]. The candidate copper alloys for fusion use to date are mainly considered to be GlidCop® and CuCrZr. The changeable material properties by neutron irradiation were summarized in four properties. The current best material for the heat sink of the FFHR-d1 could be considered to be the GlidCop®, and its temperature should be kept at 300°C without any temperature fluctuation during the operation period.

Reliable brazing combinations between "two kinds of copper alloys" and "three kinds of filler materials" were examined. The results indicate that the Nicuman37 will not be able to be used with GlidCop®, and the most superior fracture strength among three filler materials was BNi-6 with GlidCop®.

According to the brazing properties, high temperature strength, and neutron irradiation characteristics of the copper alloys, the combination of BNi-6 and the GlidCop® is the current best choice for the FFHR-d1 divertor structure, and the temperature of the GlidCop® should be kept at 300°C without changing. The brazing strength of the BNi-6 at elevated temperature such as 300°C will be investigated. Then, more reliable materials, brazing technique, and their combinations will be studied towards the final design of the divertor structure of the FFHR-d1.

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