§13. Potential of a Copper Alloy Using as a Divertor Cooling Pipe in the Helical Reactor

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The divertor armour material of the helical reactor is considering of tungsten monoblock because tungsten has large advantage for low hydrogen isotope retention, low sputtering yield. However, material selection of the cooling pipe and bonding technique between armour and pipe is currently under investigation. The copper alloy (CuCrZr) pipe was selected to use at ITER divertor because it has superior thermal conductivity. On the other hand, in heavy neutron irradiation environment like a power plant, reduced activation ferritic/martensitic steel (RAFM) such as F82H is one of the candidate material for divertor cooling pipe [1], because it has high robustness against a neutron irradiation.

However, F82H would not be able to withstand against the heat load of the divertor due to the high self-induced internal thermal stress as follows. Fig. 1-(a) shows the temperature gradient between surface and back surface of the materials as a function of an input power. Input power from the divertor plasma in the helical reactor is expected to be over 10 MW/m^2. In the case of Pure-Cu, temperature gradient (ΔT) is below 50 ˚C with a thickness of 1~1.5 mm. While, 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. Fig. 1-(b) shows the calculated induced internal thermal stress by ΔT from Fig. 1-(a) as a function of an input power. The simple equation is shown in the figure. This calculation is 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 use at this condition.

Copper alloys in heavy neutron irradiation environment cannot be acceptable because radiation defects such as dislocation loop, stacking fault tetrahedra (SFT) and void are easy to accumulate in the matrix even at low dose level (0.4~1dpa) and they lead to change the material properties [2]. The developed and assessed copper alloys so far, are categorized as an oxide dispersion-strengthened copper alloy (ODS-Cu) and a precipitation hardened copper alloy (PH-Cu). Their main properties are summarized in Table 1. Major ODS-Cu is a Al_2O_3 dispersed copper, and it has superior high temperature strength with over 300 MPa up to about 1000 ˚C. In addition, this material performs good resistivity for the radiation-induced softening and void swelling up to ~500 ˚C. However, since fabrication process must be a powder metallurgy (PM), its cost is rather high. While, leading material of the PH-Cu is CuCrZr. The yield strength of this material is drastically decreased over 400 ˚C, and limitation of the radiation-induced softening and void swelling is under 300 ˚C. Therefore, feasibility in high temperature condition is less than the ODS-Cu. However, CuCrZr has an advantage that its manufacturing process is a casting.

Determining the radiation threshold of the copper alloy under neutron irradiation is difficult because external parameters which affect to a mechanical property are various as energy spectrum, dose and irradiation temperature, and their parameters complicatedly relate to changing the material properties. The changeable material properties by neutron irradiation are (1) radiation-induced hardening/softening, (2) degradation of the thermal conductivity and (3) embrittlement by transmuted helium. These material properties directly affect the mechanical properties. The most important factor for maintaining the robustness of the materials is to keeping the toughness. First of all, radiation-induced hardening/softening is the major factor to make degradation of the toughness. 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, saturated radiation-induced dislocation loops and SFTs inhomogeneously prevent a motion of the dislocations, and thereby ability of the homogenous elongation is lost. On opposite, in the radiation-induced softening, precipitated-particles are dissociated by neutron irradiation, and obstacles for the dislocations disappear and thereby, materials to be softened.

Radiation-induced hardening/softening has temperature dependence. Its threshold temperature of ODS-Cu and PH-Cu are ~500 ˚C and ~300 ˚C, respectively. Above and below these temperatures, hardening and softening occur, respectively. The acceptable dose level of the radiation-induced hardening/softening in all copper alloy is 0.4~1dpa which is the lowest threshold in those of the above three properties [1-4]. This means that the limitation of the neutron dose to use the copper alloy is 0.4~1dpa.

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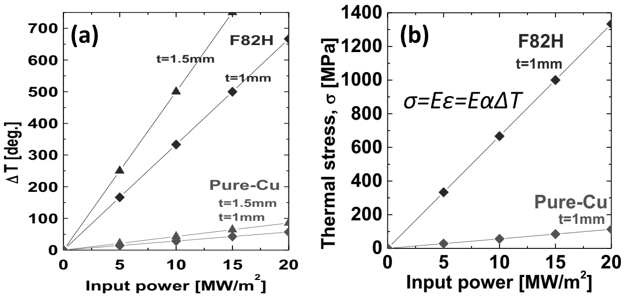

Fig. 1. (a) Temperature gradient as a function of an input power in different thickness of F82H (30W/m·K) and Pure-Cu (320W/m·K). (b) Induced internal thermal stress as a function of an input power in the 1 mm thickness of F82H and Pure-Cu. *E: Young's modulus [Pa],* α*: Thermal expansion coefficient.*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

Types of alloy	Alloy	Fabrication process	Resistance to irradiation induced softening and void swelling	Irradiation limit [dpa]	Yield strength (room temp.) [MPa]	Thermal conductivity [W/m-K]
ODS	Cu-Al_2O_3	PM -hot rolling -extrusion	< 500˚C	1dpa (< 200˚C)→ Lack of uniform elongation	> 400	~340
Precipitation -hardened	CuCrZr	Casting	< 300˚C	1dpa (< 200˚C)→ Lack of uniform elongation	> 400	~320
	CuNiBe	Casting	< 300˚C	-----	> 400	~200

Table 1. Main properties of ODS-Cu and PH-Cu alloys [2-4]