Materials Selection For HANARO Cold Neutron Source

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1. Introduction

A cold neutron source has been designed for installation in the CNS vertical hole of the research reactor, HANARO. The in-pile assembly (IPA) of the cold neutron source consists of a moderator cell containing the liquid hydrogen and a surrounding vacuum chamber. The materials for IPA are required to have good mechanical, nuclear, and thermal properties in order to withstand abnormal service conditions. In this paper, the materials used for the foreign cold sources is surveyed and described the reasons and factors underlying the choice of the materials for construction of the IPA of the HANARO cold source.

2. Materials Selection

In this section the materials used for the foreign cold sources is surveyed and the mechanical, nuclear and thermal properties of the materials are examined.

2.1 General Materials Consideration

Materials used for the construction of reactor-based cold source moderator cell and vacuum chamber worldwide are listed in the Table 1. Most of moderator cell materials are 5xxx and 6xxx Al alloys, and stainless steel (A286) is used in Orphee and JRR-3M reactors [1]. Al alloys and Zircaloy are mainly used as vacuum chamber materials. The important physical properties required for the cold source material are low neutron absorption cross sections to minimize loss of neutrons within the source, and low nuclear heating rate to reduce the cooling capacity at the source. From the engineering point of view, the materials should be compatible with the moderator medium, should have satisfactory mechanical properties at cryogenic temperatures, and should be easily available, workable, machinable, and weldable. Moreover, the materials should sustain the neutron irradiation damage at the cryogenic temperature and the low level of radiation activity is better for ease of post-service handling and disposal.

2.2 Materials Selection For The Moderator Cell

Magnesium and its alloys have generally low strength and low ductility, and their ductility is reduced to less than about 5% at low temperatures. Due to its hexagonal crystal structure, its mechanical properties are anisotropic. The anisotropic swelling and distorts were reported under neutron irradiation at about 60 ℃ in Mg alloys [1]. Magnesium is also prone to aqueous corrosion. It is assumed that the material tend to have corrosion cracking by hydrogen absorption.

Even though the effect of hydrogen on Zircaloy under irradiation at cryogenic temperature is not well known yet, the risk of the hydrogen embrittlement should be considered. Several reports pointed out the risk of the hydrogen embrittlement of Zircaloy [1, 2]. The original moderator cell made by Zircaloy in ILL had a problem with the hydrogen embrittlement. Moreover, mechanical properties of HCP structured material degrade at the cryogenic temperature compared to the room temperature.

Table 1. Materials for cold neutron sources.

Reactor	Moderator cell	Vacuum chamber
DIDO, Harwell	ZW-1 (Mg alloy)	Zircaloy-2
FRJ2, Julich	Al-3Mg (Al5754)	Al-3Mg(Al5754)
HFR, ILL	Al (99.5%)	Zircaloy-2
DR3, RISO	Al-3Mg	Al-3Mg
Orphee, Saclay	A286	AG3 NET
EL3, Saclay	Al-3Mg	-
NBSR NIST	Al6061 T6	Al6061 T6
HFBR, BNL	Al6061	Al6061
RRI, Kyoto	A5052	A5052
JRR-3M, JAERI	A286	Al6061
FRM-II, Munich	Al6061	Zircaloy-4
HFIR, ORNL	Al6061	Al6061
RRR, ANSTO	Al-5Mg	Zr-2.5Nb

Austenitic stainless steel has good mechanical properties at cryogenic temperature and is the most widely used structural material for the cryogenic application. However, the density of the stainless steel is three times larger than that of Al alloy and its thermal conductivity is only around 10% of that of Al alloy. The degree of nuclear heating scales with the mass and the density of the material. The low density materials are more advantageous than high density materials in manufacturing. Therefore, the vessel should be made thin with a material of low density and high thermal conductivity.

Aluminum has the best combination of physical and engineering properties to satisfy the requirements for a moderator cell. Aluminum has low density, high thermal conductivity, and relatively low neutron absorption cross section. It has good compatibility with the hydrogen. It can be fabricated easily, has good mechanical properties at cryogenic temperature, and has good tolerance on radiation damage.

The 5xxx Al alloy and 6061-T6 Al alloy are the most widely used alloys in the cold neutron source. The 5xxx

Al alloy has better weldability than 6061-T6 Al alloy. However, the welding of 6061-T6 Al alloy is not difficult considering the recent welding technology. The corrosion and cracking were observed in the moderator cell made by AG3 NET in Orphee reactor at a thermal neutron fluence of 8-9x10^{26}n/m^2 [1]. The similar result was reported in HFR reactor at Petten at a thermal neutron fluence of 4.5x10^{26}n/m^2. The HFIR HB-4 beam tube made of 6061-T6 Al has withstood up to the thermal neutron fluence of about 3x10^{27}n/m^2 without any signs of cracking or corrosion. These results show that the 6061-T6 Al alloy has superior irradiation tolerance to 5xxx Al alloy. 6061-T6 Al alloy is used as a moderator cell material in FRM-II and HFIR reactor. Consequently, the 6060-T6 Al alloy is the best material for moderator cell in the HANARO reactor.

2.3 Materials Selection For Vacuum Chamber

The material properties at cryogenic temperatures and the liquid hydrogen environment are important for the moderator cell. However, for vacuum chamber materials, only room temperature properties under irradiated condition are important factors. It means that disadvantages of Zircaloy-4 alloy for moderator cell material dose not apply for vacuum chamber materials. Thus, the Zircaloy-4 alloy and 6061-T6 Al alloy are two candidate materials for a vacuum chamber. HFIR chose the 6061-T6 Al alloy for a vacuum chamber material, while FRM-II chose the Zircaloy-4 alloy for a vacuum chamber material.

The Table 2 summarizes the properties of 6061-T6 Al and Zircaloy-4 alloys. The mechanical properties of Zircaloy-4 alloy are better than those of 6061-T6 Al alloy except the yield strength. The ASME pressure vessel code recommends that maximum stress inside the vessel should not exceed 2/3 of the yield strength or 1/3 of the ultimate tensile strength, whichever is the smaller. Applying this code, maximum stress of Zircaloy-4 is 25% higher than that of 6061-T6 Al alloy. The cold neutron flux increases with decreasing the vacuum chamber thickness. When hydrogen-oxygen chemical reaction occurs, the vacuum chamber have to withstand the reaction pressure. The detonation pressure is the guide pressure for deciding the thickness of the vacuum chamber. The strength data shows that the thinner vacuum chamber can be made by Zircaloy-4.

Figure 1 shows the calculated cold neutron flux with vacuum chamber thickness for 6061-T6 Al and Zircaloy-4 alloy. The neutron flux decreases by 1.8% for 1mm increase in the thickness. Comparing the neutron flux for both alloys with same thickness, the 6061-T6 Al alloy is more beneficial than Zircaloy-4 due to lower total neutron cross section. Considering both strength data and MCNP calculation result, both alloys share the merits and demerits.

Concerning procurement, machining, welding, and cost, 6061-T6 Al alloy is definitely better than Zircaloy-4 alloy. Consequently, the properties of 6061-T6 Al alloy are better than those of Zircaloy-4 alloy as vacuum chamber materials.

However, the UTS of 6061-T6 Al alloy is only 55% of that of parent material. The welding process is essential for fabrication of the vacuum chamber. The Zircaloy-4 weld has same strength level compared to the parent material in case of applying EB welding. It is of importance to conduct the careful structural analysis and the vacuum chamber design that the highly stressed region of the chamber is not located in weld part applying 6061-T6 alloy as vacuum chamber material.

Table 2. Comparison of properties of 6061-T6 Al and Zircaloy-4 alloy.

Properties	Mechanical			Nuclear	
	UTS (MPa)	YS (MPa)	Elongation (%)	Cross Section (barns)	
				σ_{abs}	σ_s
6061-T6	309	276	16.5	0.23	1.5
Zircaloy-4	413	241	14	0.18	6.5

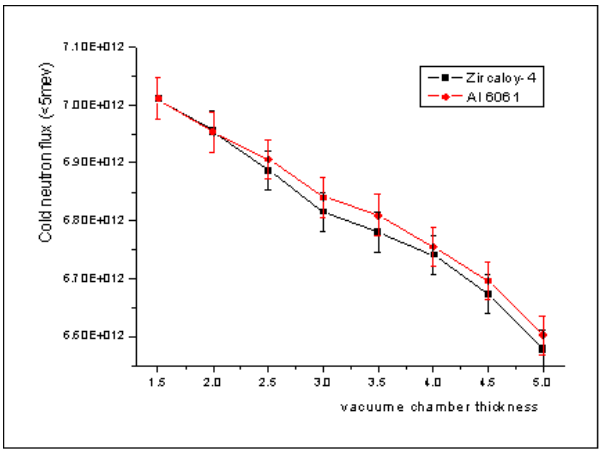

Figure 1. Calculated cold neutron flux with vacuum chamber thickness for 6061-T6 Al and Zircaloy-4 alloy.

3. Conclusion

The 6061-T6 Al alloy was selected as both a moderator cell and a vacuum chamber. For applying the 6061-T6 Alloy as vacuum chamber, careful structural analysis and the vacuum chamber design are to be performed due to weak strength of weld part.

REFERENCES

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