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Development of Basket for Transport/Storage Cask using Square Tube made of Aluminium Alloy containing Neutron Absorbing Materials

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1. Introduction

The basket of transport/storage cask must have a structural strength at any temperature expected during storage and transport condition, and must satisfy each function of sub-criticality and heat removal. It is also preferable to increase the number of fuel assemblies in the cask and to reduce the manufacturing cost.

The use of aluminium alloy for the basket is preferable because of its high thermal conductivity in order to improve heat removal. Aluminium alloy is lightweight and it is more effective to improve the capacity. The conventional design of aluminium basket had a combination of square tubes, which have structural strength and heat removal function, and the neutron absorption material with high concentration of boron.

The developed basket has square tube shape containing neutron absorption materials that has both functions of heat removal and sub-criticality. It is an effective way to improve the storage capacity of fuel assemblies and it is also easy to be assembled.

2. Targets for development of the material

The conventional storage cask basket made out of aluminium alloy cold drawn tube (A5052-H34) has been used as the structural material. We have been focusing on the following properties as the target for material development, using our experience in the design and the manufacture of the cask basket. :

(1) Reducing diameter

On the conventional design of storage cask basket, square tubes of aluminium alloy have been used as the structural material and plates with neutron absorption material have been inserted between the square tubes. In this arrangement, a structural material and a neutron absorption material must be assembled together, and there is a limit in reducing the basket diameter. Therefore, the combined material, which is able to use both structural material and neutron absorption material, was the target of our development in order to improve storage capacity.

(2) Square tube

Aluminium square tubes for the basket are preferable because it is easy to be assembled and more efficient for the heat removal. Also it can be manufactured in the almost same process as the conventional basket. Therefore we targeted a material which can be manufactured as a square tube shape.

(3) Structural strength

The structural strength should be comparable to 5052 alloy used for the conventional basket, because the thickness of the basket tube wall compared to 5052 should not be increased for space saving of the total diameter of the basket. Therefore, our target for the material strength is to go over 100MPa at 200°C considering mechanical load of basket tubes. Also the target for creep strength at the temperature higher than 200°C is at least equivalent to 5052 alloy.

(4) Thermal characteristics

The target for thermal conductivity is comparable to 5052 alloy so that spent fuel cladding temperature will be kept low during storage.

(5) Sub-criticality

Approximately 5mm thickness is necessary for the square tube considering mechanical load condition of the basket at 200°C. To keep the sub-criticality performance equivalent to the conventional basket, approximately 3mass% of boron content or equivalent quantity of neutron absorption material such as Sm should be contained in the material for this wall thickness.

3. Design feature

Non-heat treatable aluminium alloy 5052 has been used as the conventional basket material and has enough strength for the cask basket because of Mg contained in this alloy. Therefore, it can be expected that the material strength of 5052 alloy will not decrease significantly even during the long-term storage estimated for the cask under the elevated temperature. Our development target of the strength is equivalent to 5052 alloy, the strength improvement of the material was designed in the same way as the 5000 series alloy which contains Mg. The additional element for age hardening, such as Cu and Si was not contained in this alloy, because the significant strength reduction at the elevated temperature for long-term storage must be avoided.

Two different metallurgical approaches to add boron in aluminium alloy are known, adding B into molten aluminium at casting process known as I/M (ingot metallurgy) process and mixing the stable compound such as B_4C with aluminium alloy powders known as P/M (powder metallurgy) process. I/M process is already adopted in case of 1000 and 6000 series alloys, it is difficult to apply to 5000 series alloys due to Mg which forms intermetallic compounds with boron. Therefore, P/M process, in which B_4C is mixed with Al alloy powder, is adopted to add the necessary amount of boron to the alloy. When the significant amount of B_4C is added to the aluminium alloy, there are difficulties for such manufacturing processes like extrusion to form a square tube and cutting after extrusion because of the extreme hardness of the B_4C. So, it is more advantageous to use less B_4C during the manufacture process.

Gd, Sm, Hf, Cd, etc. are known as neutron poison materials. In order to reduce the amount of B_4C, improvement of sub-critical performance by adding small quantity of these elements has been investigated. Properties of aluminium alloys containing neutron poison additives other than the neutron absorption characteristics, such as formability during extrusion, mechanical properties, manufacturing cost, and so on were also examined. Sm has been selected as an additional element as a result. The improvement of strength and stability at elevated temperature can also be expected if rare earth element such as Sm is added to aluminium alloys.

Since Sm is a much heavier element compared with Al and Mg, and Sm is not easy to be contained in the Al matrix as a solid solution, it is very difficult to obtain homogeneous microstructure when it is manufactured by I/M process which has a slow cooling rate after casting. In this development, rapidly solidified powder metallurgy process was chosen to produce Al-Mg-Sm alloy powders. Gas atomization process is applied to produce the aluminium alloy powders and hot extrusion method is applied to manufacture the square tube.

The chemical composition of the alloy has been considered from a viewpoint of sub-criticality, mechanical strength at elevated temperature and manufacturing cost. As a result, it has been decided that Al alloy composition is approx. 5% Sm- approx. 2% Mg- approx. 2.3% B_4C.

4. Material characteristics

The developed basket alloy was manufactured from more than 3 different lots and necessary examinations after extrusion process were carried out. To evaluate the properties of temperature dependence, examinations were carried out in the range from room temperature to 300°C.

(1) Chemical composition

Chemical analysis has been performed by ICP (Inductively Coupled Plasma) emission spectrometric analysis. The measured value of the principle element of the developed alloy is shown in the table 1. It was also confirmed that chemical composition is almost equal to any position of the tube, and in any lots of material.

Atomic densities for sub-criticality analysis with appropriate margin will be assumed after production evaluation and neutron permeation test.

(2) Thermal conductivity

The laser flash method has been applied to measure the thermal conductivity. Temperatures dependence of the thermal conductivity are given in the figure 1. It was also confirmed that there is no difference between the thermal conductivities at any position of the tube and in any. Also, it was confirmed that the developed alloy shows little bit higher conductivity values at any temperature compared with the 5052 alloy shown in the figure 1. Mg is very easy to be solid solution in aluminium matrix and the solute atom is known to decrease the thermal conductivity. The reason why that 5052 alloy shows lower value of thermal conductivity is due to its higher amount of Mg (approximately 2.5mass%) compared to the one contained in the developed alloy (approximately 2.0mass%).

(3) Elastic modulus

Measurement of elastic modulus has been carried out by bending resonance method. Relations between elastic modulus and temperature are shown in the figure 2. It has been confirmed that no difference was observed in any lots as well as the chemical compositions. It has been confirmed that the characteristic of elasticity was equivalent to 5052 alloy within 5-10% range as shown in the figure 2. However, the value is slightly higher in comparison with 5052 alloy, there is no significant influence in structural properties.

(4) Metallurgical feature

The optical microstructure after extrusion processing is shown in the figure 3. The black particles in the pictures were identified to be B_4C and its homogeneous distribution in the microstructure can be easily observed. It has been also confirmed by EPMA analysis that Sm was dispersed uniformly in the matrix and this is because the alloy was manufactured using atomization method in which produced powders have very high cooling rate (10^3-10^5K/sec) compared with usual casting (10^{-2}-10^1K/sec).

(5) Structural characteristics

The temperature dependence of 0.2% proof stress of the developed alloy is shown in the figure 4. That of 5052 alloy is also given in the figure 4. The temperature dependence of ultimate tensile strength of the developed alloy is shown in the figure 5. That of 5052 alloy is also shown in the figure 5. The temperature dependence of elongation of the developed alloy is shown in the figure 6. That of 5052 alloy is also given in the figure 6.
In the figure 4, 5052 alloy shows significantly higher value of proof stress compared to the developed alloy, especially at low temperature, this is because strength of A5052-H34 is including work hardening. It is found that ultimate tensile strength of the developed alloy was almost equivalent to the 5052 alloy at any temperature in the figure 5. It has been confirmed that tensile properties of the developed alloy were almost equivalent to the 5052 one's.

(6) Creep strength

As the temperature of the basket in the actual use becomes approximately 200°C, creep-rupture test were carried out because influences of creep have to be considered at this temperature range for aluminium alloys.
The result of steady state creep strength put in order in the Larson-Miller parameter is fitted to the equivalent result of the 5052 alloy in the figure 7. Moreover, the result of creep rupture strength put in order in the Larson-Miller parameter in the same way is fitted to the equivalent result of the 5052 alloy in the figure 8.
It has been confirmed that the developed alloy has almost equivalent or higher creep strength compared to 5052 alloy in high LMP range of LMP>approx.12×10^3 as shown in the figure 7. LMP=12×10^3 is equivalent to about 26 years at the temperature of 200°C. Though the creep strength of 5052 alloy is higher in low LMP range of LMP<approx.12×10^3, the reason of this effect will be the influence of the work hardening of 5052 alloy as stated in (5) above.

(7) Corrosion resistance

During storage, there is few possibility of corrosion because of He atmosphere, although the condition of a basket is expected to be approximately 200°C. At the first step of for loading the spent fuels, the basket material has a chance to contact with pool water at reactor site. Also there is a possibility to contact with water that contains boric acid, in the case of the PWR plant. Though it is said that aluminium alloy containing Mg has high resistance to corrosion, the effects of Sm and B_4C added to aluminium alloy are unknown. So, the corrosion experiment was

conducted under boric acid solution, and corrosion resistant of this material is evaluated in comparison with 5052 alloy.
An accelerated corrosion test condition shown in the table 2 was decided by assuming the pool water of the PWR plant. The temperature was decided considering the exposure in the vacuum drying process. The surface condition after examination in the above mentioned atmosphere for one month is shown in the figure 9. A surface is a little corroded due to the environment of the weak acidity. The corrosion depth of 5052 alloy was approximately 30µm and the one of the developed alloy was approximately 60µm. The corrosion depth of the developed alloy was slightly greater than the one of the 5052 alloy due to containing B_4C particles in the developed alloy, but the corrosion resistance of matrix did not defer significantly. This fact shows that the corrosion resistance of the developed alloy has not any problems under actual condition because only a little corrosion was observed under severe atmosphere in comparison with actual condition.

Moreover, other examinations such as measurement of coefficient of thermal expansion, hardness test and impact strength were carried out, and it was confirmed that the developed alloy has the equivalent characteristics to 5052 alloy as well.

5. The trial manufacture of the square tube and design of the basket

The trial manufacture of the square tubes is conducted for actual size of BWR fuel basket. The dimension of the square tube was set up in accordance with the aforementioned characteristics of structural strength, sub-criticality performance, etc. The dimension of inside opposite surface is 150mm, the entire length is 4400mm, and proper tolerance is set up toward the bend and so on.
Material is formed to billet shape after atomized Al-Mg-Sm alloy powder and B_4C were mixed uniformly. This billet was extruded at elevated temperature and a square tube was formed (figure 10). It was confirmed that the square tubes satisfied the dimensions and the tolerance requirement, and there was no harmful defect.

With the application of this square tube, the fuel channels of the basket are used as not only a neutron absorption material, but also as a structural material. It is possible to assemble a basket using only this aluminium alloy square tubes without extra neutron absorption material positioned between aluminium alloy square tubes. Moreover, the reduction of manufacturing cost and steps of manufacturing process is expected because the process of such as slit cutting or welding is not necessary for this square tube. The design example of the basket for BWR fuel, using this square tube, is shown in the figure 11.
In case the basket shown in this figure is used for transport/storage cask, brief safety evaluations are performed as transport cask such as a thermal test, 9m drop test and sub-criticality. As the result of thermal analysis shows that the maximum temperature of the basket is approximately 250°C even in the thermal test, it has been confirmed that the basket has a good ability of heat removal. As for the structural analysis for the drop test, it has been confirmed that the evaluated stress of the basket is below the material proof stress. As for the sub-criticality, it has been confirmed that the effective multiplication factor (keff) will not exceed 0.95 with the fuel of initial concentration of 3.6% (average).

6. Summary

A material which unified structural material and neutron absorber, and which has enough thermal conductivity, structural characteristics etc. and is equivalent to 5052 alloy, has been developed. The basket has been developed, which have a good ability of heat removal, structural strength and sub-criticality with assembling the square tubes using this material.
Therefore, before going into production and by taking into account those parameters, significant cost reduction can be achieved.

Table 1 Major Chemical Composition

Unit : mass%

Lot No. of Sample	Mg	Sm	B	Others (Al, etc.)
1 H	2.05	5.55	1.77	Bal.
1 M	2.04	5.52	1.82	Bal.
1 T	2.03	5.56	1.97	Bal.
2	2.02	5.52	1.85	Bal.
3	2.03	5.53	1.89	Bal.
4	2.01	5.46	1.95	Bal.
5052 （reference）	2.2~2.8	-	-	Bal. (Si, Fe, Cu, Mn, Cr, Zn, Al)

The name of “H”, “M” and “T” indicate a part of sample at Head, Middle and Tail.

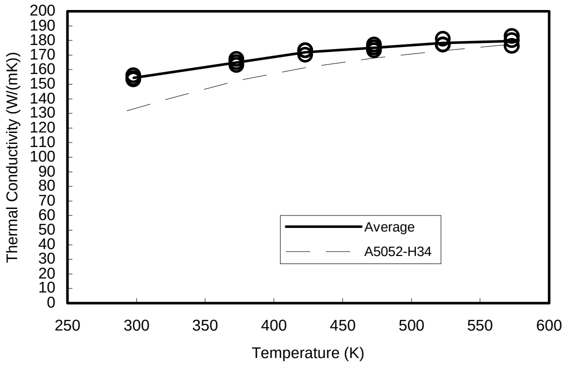


Fig. 1 Relation between thermal conductivity and temperature

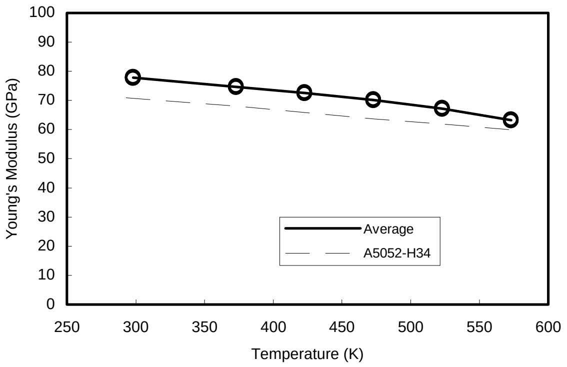


Fig. 2 Relation between young’s modulus and temperature

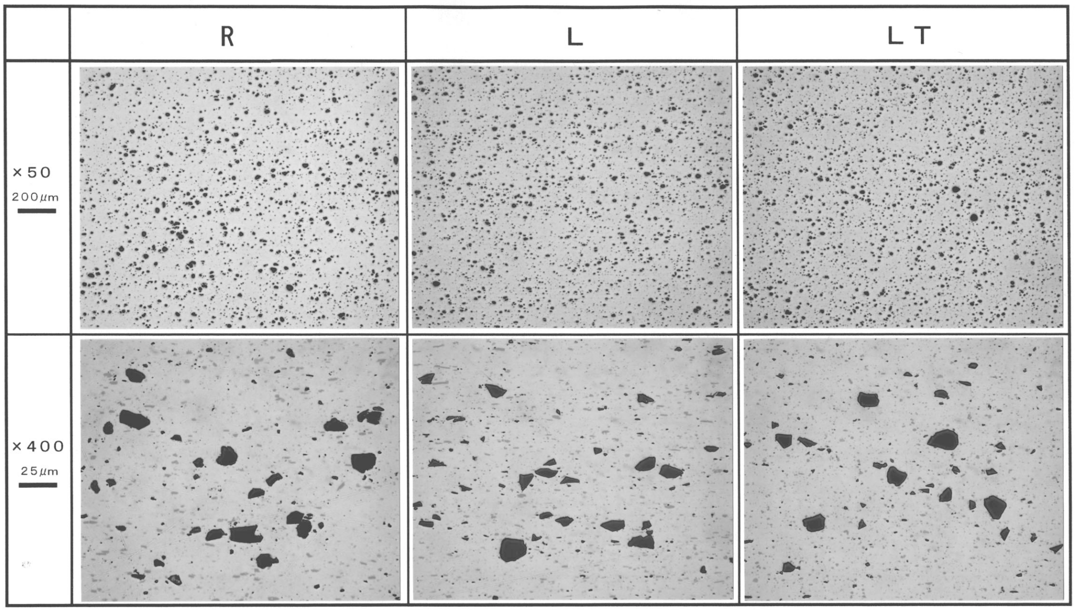


Fig. 3 Typical microstructure

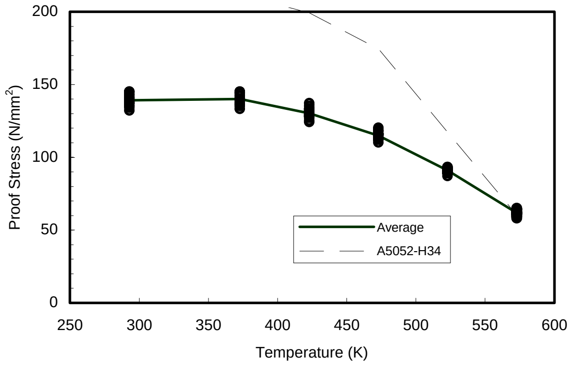


Fig. 4 Relation between proof stress and temperature

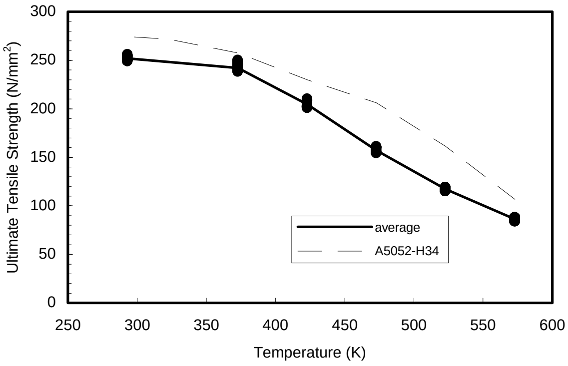


Fig. 5 Relation between ultimate tensile strength and temperature

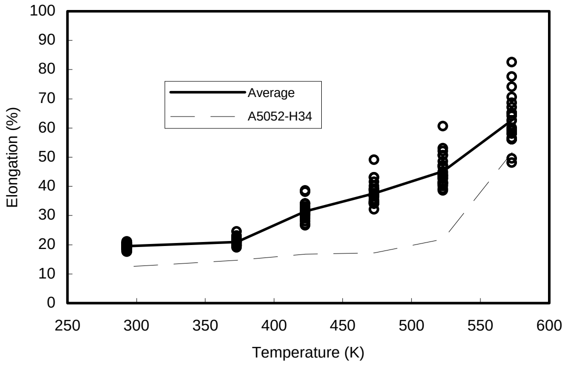


Fig. 6 Relation between elongation and temperature

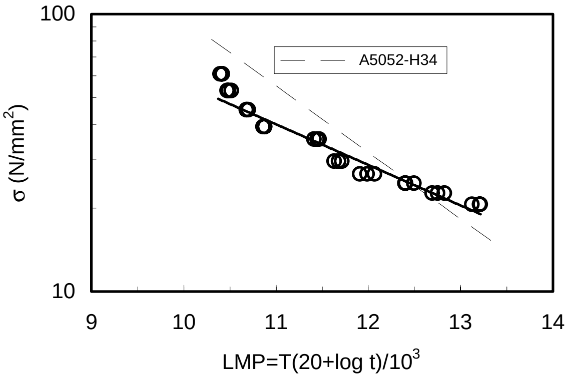


Fig. 7 Larson-Miller Plot of stress-rupture data

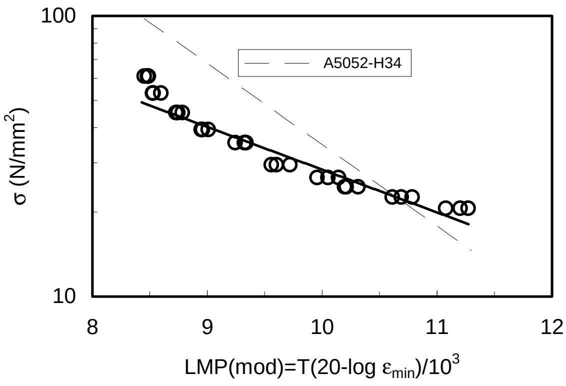
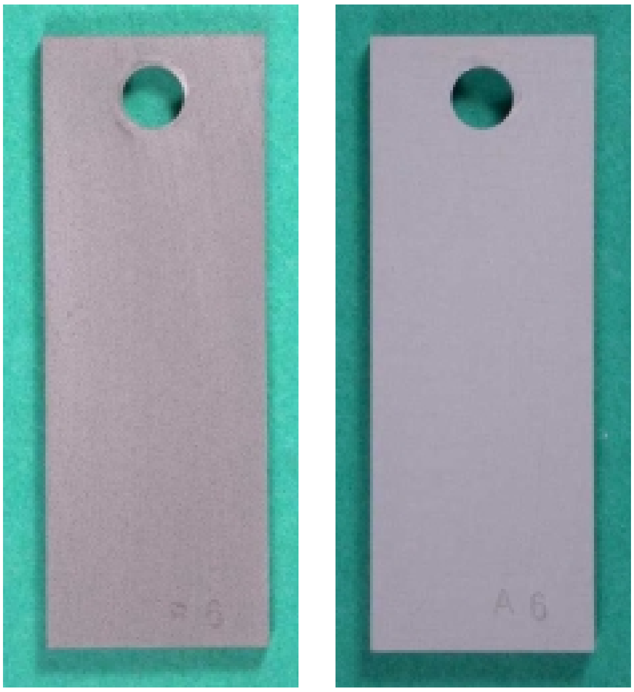


Fig. 8 Larson-Miller (mod) plot of creep data

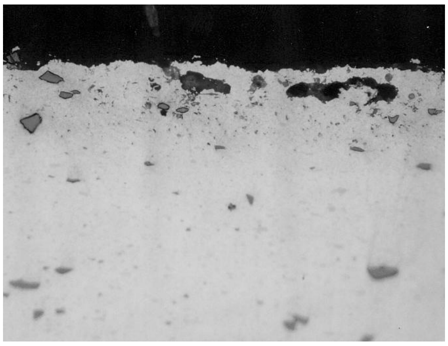
Table 2 Comparison of corrosion atmosphere with actual and test condition

	Actual condition	Test condition
Solution	Pool water (in the PWR plant) → Vacuum drying	Boric acid solution of 2000ppm (Mock liquid of PWR pool water)
Temperature	Approx. 50°C (in pool) ~ 200°C (drying)	200°C
Time	Approx. 1week (in pool)	1 month

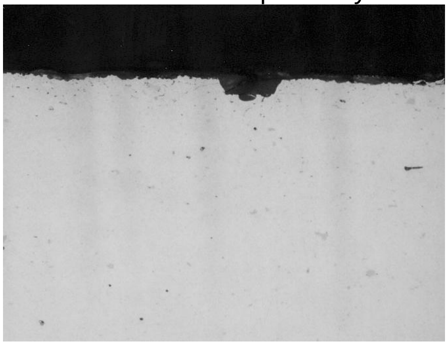


Specimen of the developed alloy

Specimen of 5052 alloy



Cross-sectional microstructure of the developed alloy



Cross-sectional microstructure of 5052 alloy

Fig. 9 Comparison between the developed alloy and 5052 alloy after corrosion testing

Fig. 10 Sample of square tube in actual size for BWR fuel basket

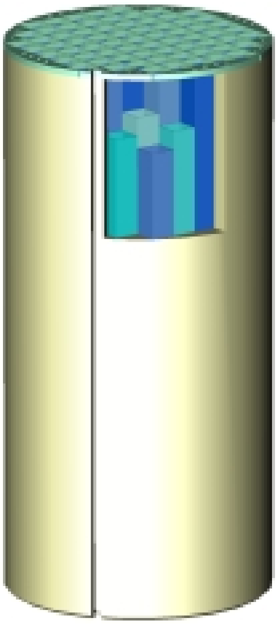


Fig. 11 Typical design of BWR fuel basket using square tubes