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DEVELOPMENT OF BORATED ALUMINUM MATERIAL FOR BASKET OF TRANSPORT/STORAGE CASKS

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ABSTRACT
Enriched borated aluminum alloys suitable for application to baskets in transport and storage casks for high burn-up spent fuels have been developed. This borated aluminum alloy is 1mass%B-A6061-T6 and various design basis properties required for cask basket has been prepared. The various properties such as neutron absorption, thermal conductivity, mechanical property and fracture toughness were taken into consideration to develop the borated aluminum alloy. And the allowable stresses of 1mass%B-A6061-T6 have been evaluated according to the draft of "Rules on Transport / Storage Packagings for Spent Nuclear Fuel" being now prepared by the Japanese Society of Mechanical Engineers.

INTRODUCTION
The basket of transport and storage cask must have a structural strength during transport and storage conditions, and must satisfy each function of sub-criticality and heat removal. The basket material is also preferable to be light in order to reduce the weight of cask because it is very important to increase number of fuel assemblies loaded in the cask for efficient transport and storage. The aluminum alloy is the suitable base material for the basket due to its low density and high thermal conductivity and it could reduce the weight of cask and effectively transfer the heat generated by spent fuels. Borated aluminum alloy is one of the most important materials and widely used for the basket of dry spent fuel casks because of its excellent thermal conductivity and lighter weight etc. The maximum boron content in aluminum alloy is limited up to a few mass percent at most, however borated aluminum alloy can have high neutron absorbing performance by using enriched ^{10}B and keep the package with fuel assemblies sub-critical.
Borated aluminum alloy is not specified as a standard material, but in Japan, "Rules on Transport / Storage Packagings for Spent Nuclear Fuel" being now prepared by the Japanese Society of Mechanical Engineers. In this code, the rule for registration of new material is specified. Accordingly, the required mechanical properties of this material for the cask basket design have been evaluated such as mechanical properties at elevated temperature, mechanical properties after long term aging taking into account storage period, long term creep properties and fracture

toughness, etc. and the allowable stresses of 1mass%B-A6061-T6 have been evaluated according to this code.

MANUFACTURING METHOD

Chemical composition of this borated aluminum ally is shown in Table1.Chemial form of boron compound included in this material, 1mass%B-A6061-T6, is AlB_2. For keeping sub-criticality of fuels in a cask, it is preferable that these compound particles are fine and uniformly distributed in the basket material. In order to manufacture such material, it is very important to control the conditions of melting temperature, agitating of molten material and casting.

There are two manufacturing methods to make ingot of borated aluminum alloy. The one is vacuum induction melting and casting method, which can melt boron compounds completely at high temperature, more than 1000 ^{o}C and it is extremely effective to make fine boron compounds by casting with the proper cooling speed [1, 2]. This method is especially effective for relative low content borated aluminum alloy in case such as 1 or 2 mass% borated. However, when the melting temperature of boron compounds becomes higher (1300-1500 ^{o}C) with higher boron content increased such as 3 or 4 mass% [3] , boron compounds become easy to enlarge during crystallizing process of casting and cooling. The other one is DC casting method with melting relative low temperature (several hundreds) in open atmosphere, which does not melt boron compounds completely but contains them as fine particles in molten aluminum. It is applicable for any content of borated aluminum and has advantage of manufacturing cost compared with vacuum induction melting method. It is confirmed that the both borated aluminum alloys have the same mechanical properties regardless of these manufacturing methods.

The good results are obtained as shown in Figure 1 and 2. It was confirmed that it had fine particles of several microns of boron compound in microscopic point of view, and good dispersion of them in macroscopic.

Table 1. Chemical composition of borated aluminum

Alloy	B	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti
1 mass%B -A6061	0.6 - 1.1	0.40 - 0.80	< 0.70	0.15 - 0.40	< 0.15	0.8 - 1.2	< 0.25	0.04 - 0.35	< 0.15

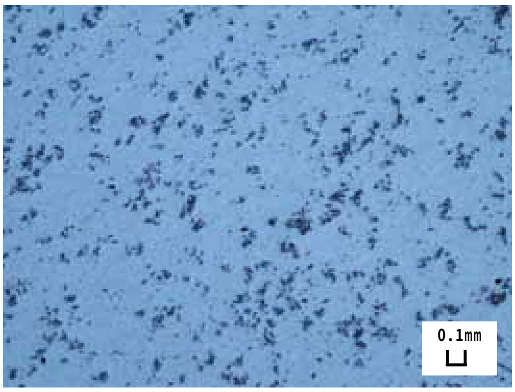
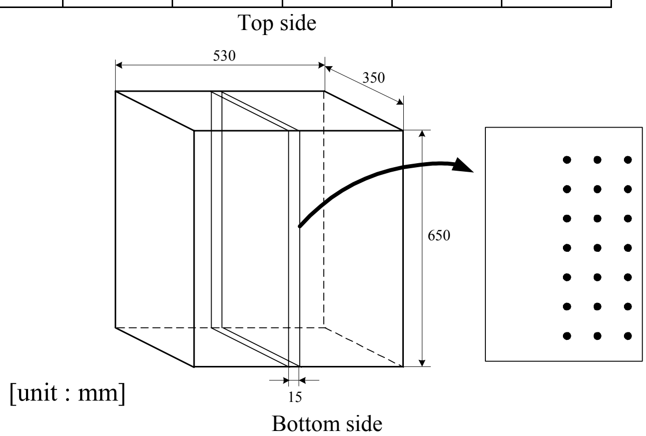


Figure 1. Microstructure of borated aluminum ingot



< Sampling positions for Boron analysis >

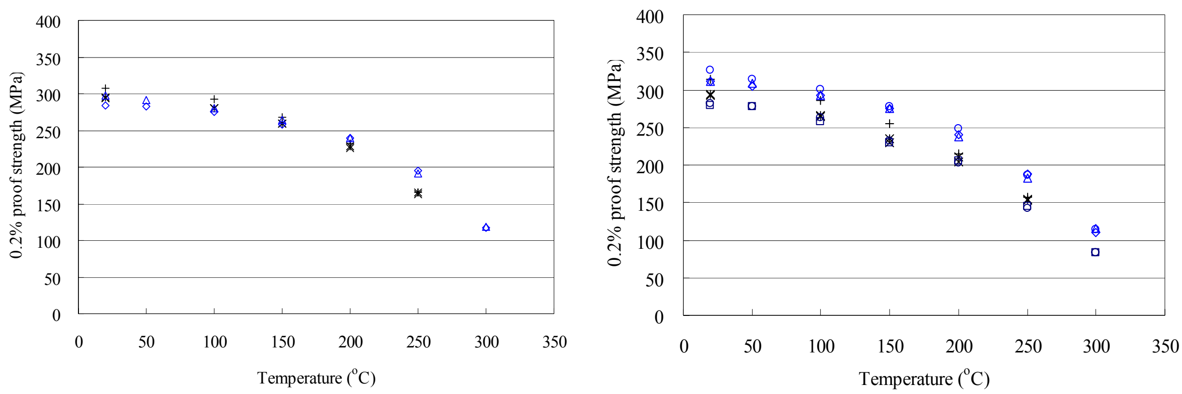
Allowable range	0.6 ～ 1.1 mass%
Result of boron analysis	0.8 ～ 1.1 mass% (21 positions)

Figure 2. Macroscopic distribution of boron content

MECHANICAL PROPERTY

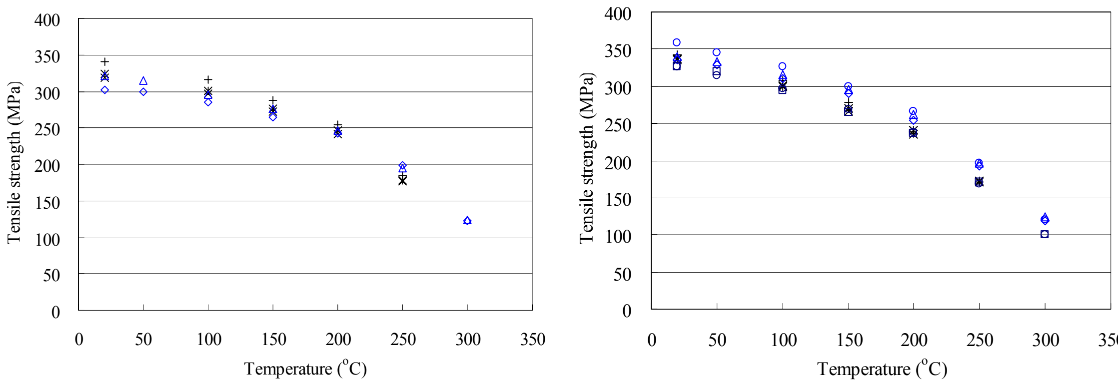
Mechanical Property at Room and Elevated Temperature

The tensile mechanical properties of 1mass%B-A6061 and ordinary A6061-T6 plate materials were evaluated at room and elevated temperatures. The reason A6061 is selected as base alloy is that 6000 series alloys are heat treatable and have moderately high strength coupled with excellent corrosion resistance. 0.2% proof strength and tensile strength are shown in Figure 3 and 4 respectively. The tensile properties of 1mass%B-A6061 are a little higher than those of ordinary A6061-T6 but it is confirmed that these are similar properties.



(a) A6061-T6 **(b) 1mass%B-A6061-T6**

Figure 3. 0.2% proof strength at elevated temperature



(a) A6061-T6 **(b) 1mass%B-A6061-T6**

Figure 4. Tensile strength at elevated temperature

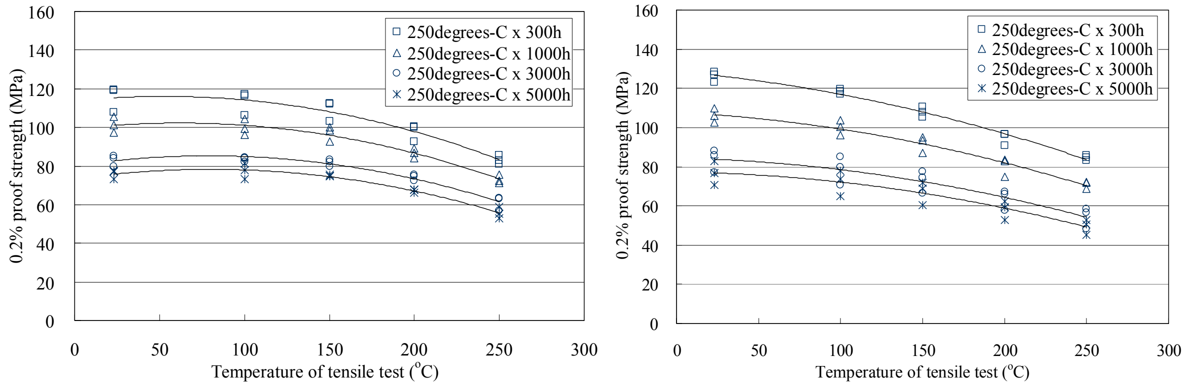
Mechanical Property after Long Term Aging

The mechanical property of aluminum alloy is generally known to be decreased with kept at elevated temperature. And the borated aluminum alloy used for basket of cask will have been exposed to atmosphere of approximately 200 °C in maximum during storage period. Therefore it is necessary to evaluate, in advance, the tendency of decreasing rate of the strength for the basket design. Accordingly, tensile tests of aluminum alloys with long term aging were performed. The test conditions are listed in Table 2 and the test results are shown in Figure 5 and 6. It was confirmed that the tensile properties were significantly decreased by long term aging because the

Mg_2Si particles, which strengthen the 6000 series aluminum alloys by crystallizing finely in the base aluminum material, were grown too big [4)]. However, these tendencies of decreasing strength are possible to be estimated using Larson-Miller parameter. The allowable strengths for design such as 0.2% proof strength; Sy, tensile strength; Su and design stress intensity; Sm can be determined by evaluating mechanical properties of aged material on the accelerated conditions with the same Larson-Miller parameter of the actual usage conditions.

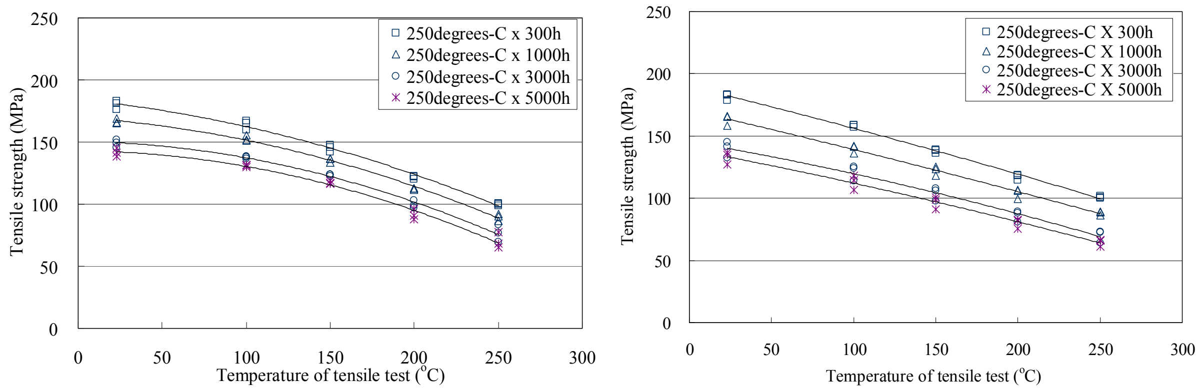
Table 2. Aging condition

	Condition
Material	A6061-T6 1mass%B-A6061-T6
Number of Material	3 lots
Number of test specimen	3 per condition
Temperature	250°C
Aging period	300h, 1000h, 3000h, 5000h



(a) A6061-T6 **(b) 1mass%B-A6061-T6**

Figure 5. 0.2% proof strength of aged alloy

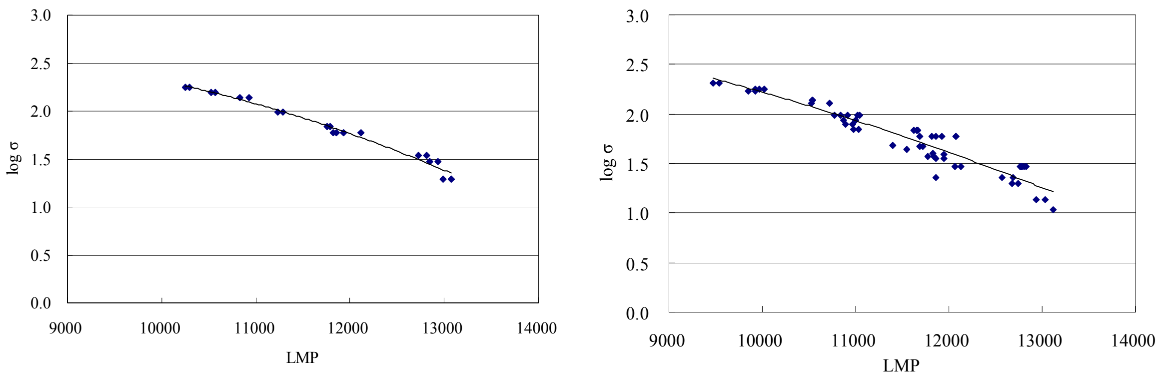


(a) A6061-T6 **(b) 1mass%B-A6061-T6**

Figure 6. Tensile strength of aged alloy

Creep Property

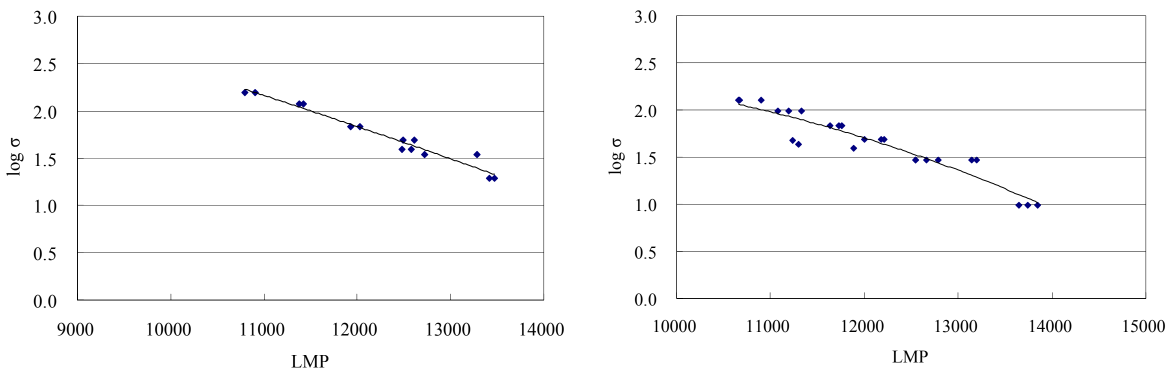
Creep tests were conducted at temperature between 150 °C and 300°C in constant load machines at the various stresses from 9.8MPa to 207MPa. Figure 7 and 8 show the Larson-Miller plots of creep rupture stress and steady state creep rate, respectively. As shown in these figures, it is also confirmed that 1mass%B-A6061-T6 has similar creep properties. Using these data, the stresses of 100,000 hours creep rupture and steady state creep rate of 0.01%/1000hours can be extrapolated for setting the maximum allowable stress value; S.



Note : LMP=(T+273.15)x(20+log t), T:temperature / t:creep rapture time

(a) A6061-T6 **(b) 1mass%B-A6061-T6**

Figure 7. Results of creep rupture test



Note : LMP=(T+273.15)x(20-log ε) , T:temperature / ε:steady state creep rate

(a) A6061-T6 **(b) 1mass%B-A6061-T6**

Figure 8. Results of steady state creep rate

Fracture Toughness

Borated aluminum alloy has rather small elongation than ordinary aluminum alloy because of the boron compounds in the matrix alloy. Therefore, static and dynamic fracture toughness tests were conducted in order to confirm that 1mass%B-A6061-T6 has enough fracture toughness and no brittle fracture property by impact force of 9m drop test condition. Test conditions and results are shown in Table 3, Table 4 and Figure 9 respectively. In these results, the static and dynamic K_Q values ware almost same and independent of loading rate. These K_Q values were almost equal to the calculated K_{Ic} from valid J_{Ic}. It was also confirmed that the fracture mode of this material was not cleavage fracture but micro-void coalescence type. In this test, after the first fracture was caused by micro-void coalescence type crack, it steadily progressed with increasing J value.

Therefore this material is not broken unstably even on condition of the impact force such as 9m drop test. To evaluate dynamic fracture toughness at low temperature, for example -20^{o}C, will be performed.

Table 3. Test conditions of fracture toughness

	Condition	
	K_{Ic} and K_{Id}	J_{Ic}
Material	1mass%B-A6061-T6	1mass%B-A6061-T6
Material thickness (mm)	10	10
Specimen shape	Compact specimen	Compact specimen
Stroke speed (mm/sec)	0.008 / 20 / 200	Static
Temperature	Room temperature	Room temperature
Test procedure	ASTM E399-90	ASTM E1820-90

Table 4. Test results of fracture toughness

	Evaluated data	Remarks
Valid J_{Ic} (kJ/m^2)	9	
K_{Ic} (MPa*m$^{1/2}$)	26	Calculated from Valid J_{Ic}

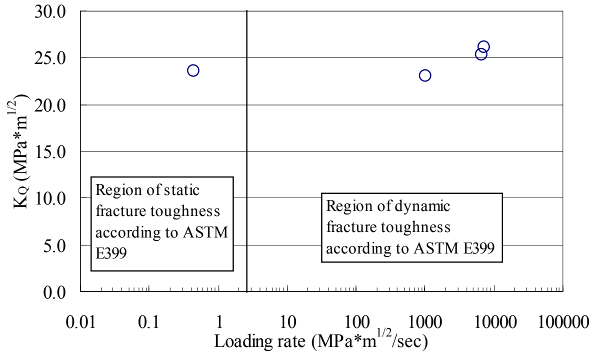


Figure 9. Relation of K_Q and loading rate

<u>Other Properties</u>

Elastic modulus, Poisson's ratio, specific heat and thermal conductivity at elevated temperatures are shown in Figure 10, 11, 12 and 13 respectively. It was confirmed that these properties of 1mass%B-A6061-T6 are similar to those of ordinary A6061-T6 alloy.

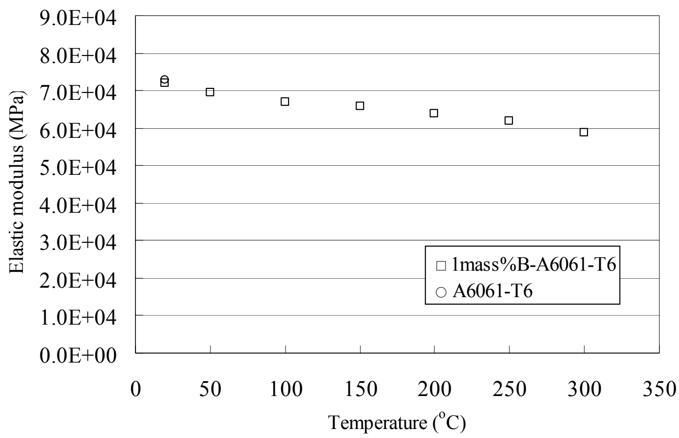


Figure 10. Elastic modulus at elevated temperature

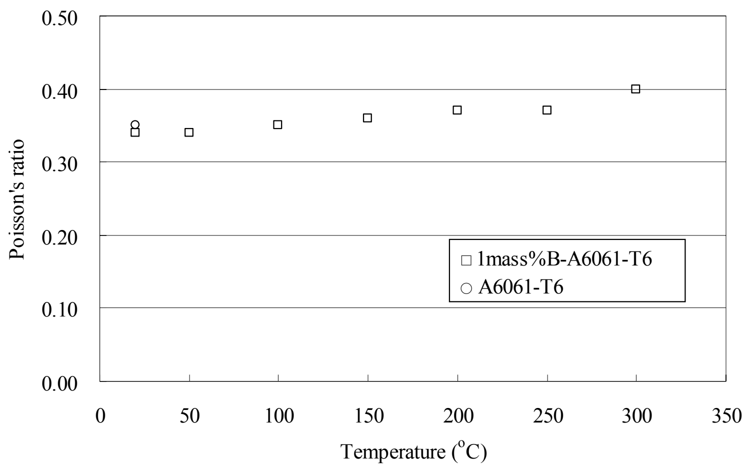


Figure 11. Poisson's ratio at elevated temperature

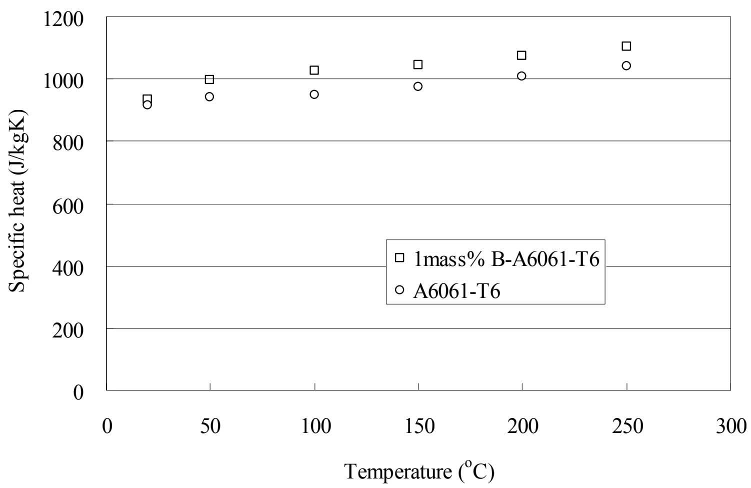


Figure 12. Specific heat at elevated temperature

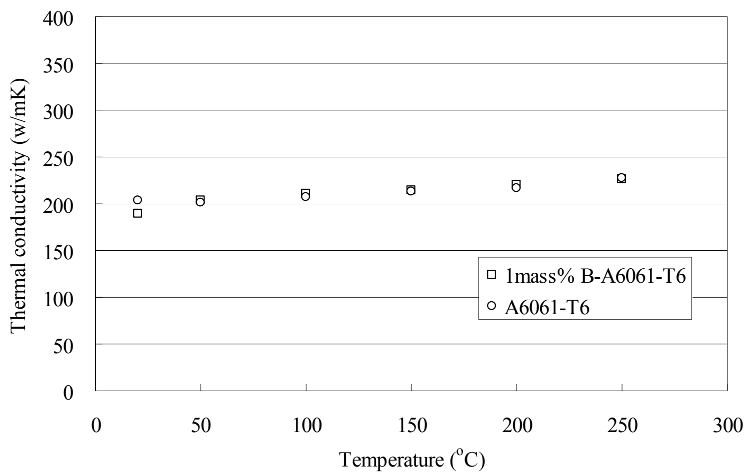


Figure 13. Thermal conductivity at elevated temperature

ALLOWABLE STRESS

Allowable strengths were determined using evaluated data mentioned above. The procedure was according to the draft of "Rules on Transport / Storage Packagings for Spent Nuclear Fuel" which is now being prepared by the Japanese Society of Mechanical Engineers. Allowable stresses of A6061-T6 and 1mass%B-A6061-T6 are shown in Table 5 and 6. These values were evaluated assuming that Larson-Miller parameter was 12000, which means that basket materials will have been exposed to atmosphere of maximum 195 ^{o}C in constant during storage period of 60 years. Actually speaking, the temperature of materials will be gradually decreased during storage, therefore assumption of the maximum constant temperature is conservative evaluating condition.

Table 5. Allowable stress of A6061-T6

	Temperature (^{o}C)						
	R.T.	50	100	150	200	250	300
Tensile strength, Su (MPa)	147	147	147	131	111	86	57
0.2% proof strength, Sy (MPa)	93	93	93	89	80	68	52
Design stress intensity, Sm (MPa)	49	49	49	44	37	29	19
Maximum allowable stress, S (MPa)	42	42	42	37	32	11	2

Table 6. Allowable stress of 1mass%B-A6061-T6

	Temperature (^{o}C)						
	R.T.	50	100	150	200	250	300
Tensile strength, Su (MPa)	156	156	146	128	110	92	73
0.2% proof strength, Sy (MPa)	95	93	89	82	73	63	50
Design stress intensity, Sm (MPa)	52	52	49	43	37	31	24
Maximum allowable stress, S (MPa)	45	45	42	37	26	8	2

CONCLUSIONS

The required mechanical properties of 1mass%B-A6061-T6 for the cask basket design have been evaluated and it was confirmed that this material has the similar mechanical and thermal properties of ordinary A6061-T6. The allowable strengths were determined using evaluated data according to the draft of "Rules on Transport / Storage Packagings for Spent Nuclear Fuel" which is now being prepared by the Japanese Society of Mechanical Engineers.

ACKNOWLEDGMENTS

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