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Development of Aluminum Extruded Alloy for Basket of Transport/Storage Casks (2)
- Properties and allowable stress of the borated aluminum alloy 1B-A3J04-O -

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ABSTRACT
Basket material of transport and storage casks is required to have enough structural strength under transport and storage conditions to maintain safety functions such as sub-criticality and heat removal. The material is also preferable to have low density to reduce the weight of cask because it is very important to increase the capacity of fuel assemblies loaded in casks in order to improve the efficiency of spent fuels transportation and storage. Aluminum alloy is the suitable material for a basket due to its low density and high thermal conductivity resulting in weight reduction and better heat transferring capability. A new extruded borated aluminum material has been developed, that is the Al-Mn-Mg alloy with about 1% enriched boron. The base alloy is similar to A3004 alloy but the content of the minor added elements such as Si, Fe, Cu and Zn were reduced compare with the normal A3004 alloy. In addition, this material receives annealing, i.e. the O-state heat treatment. Therefore, almost no change will occur on its strength during the long-term storage up to 60 years.

1. INTRODUCTION
For the basket design of the transport and storage cask, the degradation during the long-term storage should be considered because it will be operated as the transport cask after the storage. In Japan, the interim storage period of casks is considered up to 60 years. Aluminum alloy is the suitable material for a basket because of its low density and excellent thermal conductivity. However the aluminum basket material may have the possibility to reduce the strength due to the heat history during long-term storage, therefore it is very important to evaluate its strength after the storage with proper methods in order to design the basket of transport and storage cask.

Kobe Steel, Ltd. had developed two borated aluminum alloys i.e. the rolled material “1%B-A6061-T651” and the extruded material “1%B-A3004N-H112”. But it is not easy to evaluate the strength of these materials because their strengths will be decreased after the storage period [1], [2]. This time, Kobe Steel, Ltd. has developed the new extruded material “1B-A3J04N-O”, that is the Al-Mn-Mg alloy with about 1% enriched boron. The new material is based on the

1%B-A3004N-H112 and has been modified to maintain the strength during the long-term storage up to 60 years. This material is an optimum material for the basket with water gaps for PWR fuels because it can be manufactured with various cross-sectional shapes by extruding. It also has high neutron absorbing performance because of its high content of boron-10 by using enriched boron, and the thermal conductivity is same as that of the base material because the boron content is limited to about 1%. The mechanical properties such as the tensile strengths, fracture toughness in elevated temperatures and the effect of aging during storage, etc. has been evaluated from the design point of view for the cask basket.

2. CHARACTERISTICS OF 1B-A3J04-O

The chemical composition of this borated aluminum alloy is shown in Table1. Mn and Mg are added as the main element, therefore this material mainly has the two strengthening mechanisms, i.e. the particle dispersion strengthening by Mn compounds and the solid solution strengthening by Mg. Other minor elements such as Si, Fe, Cu and Zn are reduced compare with normal A3004 alloy. And this material has been annealed, i.e. the O-state heat treatment, in order to prevent the strength reduction after the long-term storage up to 60 years. The detail about chemical composition and strengthening mechanisms are described in the other paper [3].

3. MANUFACTURING METHOD

This material is manufactured with the normal hot extruding method as follows.

- ✓ Billet by the direct chilled casting
- ✓ Homogenized heat treatment (500-560^{o}C x 4h min.)
- ✓ Extruded by the press machine
- ✓ Stretched to make the extruded material straight
- ✓ Annealing to relief work hardening (350-410^{o}C x 2h min.)

4. TEST SPECIMEN

The chemical analysis results of the test specimens are shown in Table 2 and Table 3. There are two kinds of test specimens prepared. One is the material of which chemical contents such as Mg, Mn, Si and Fe are set almost lower limits of each chemical range to evaluate the mechanical properties conservatively (here after the material is called “Material for mechanical property”), the other one is the material of which chemical contents such as Mg, Mn, Si and Fe are set the medians of each chemical range to evaluate other properties such as elastic modulus, liner expansion coefficient and thermal conductivity, etc. averagely (here after the material is called “Standard material”).

The cross-sectional shapes are shown in Figure 1. There are two kinds of shapes prepared. One is the flat bar of solid type and the other is the hollow type. The flat bar type is used for a basket of BWR fuels and the hollow type is used for that of PWR fuels.

5. MECANICAL PROPERTY

Initial Material

To evaluate the specified strengths at room temperature of initial material, tensile tests at room temperature were conducted without the long-term heat treatment (described in the next section). For this evaluating test, the Materials for mechanical property were used. The tests procedure is according to JIS Z2241. The evaluated specified strengths at room temperature, i.e. the criteria of the strength for product materials, are shown in Table 4. These specifications are evaluated as the lowest values including 99% reliability, i.e. average value -2.33 σ (σ :standard deviation), and with rounded down conservatively. As for the specified elongation, it is also evaluated as the lowest values including 99% reliability, and with taking some margin into considerations. In the evaluations for these specifications, it is confirmed that the plots with normal probability have the almost linear profile.

Long-term Heat Treatment Material

To evaluate the allowable stresses in each elevated temperature, the equivalent heat treatment should be conducted for the test specimens with taking the heat history up to 60 years into account. For these evaluating tests, the Materials for mechanical property were used to evaluate them conservatively. The heat treatment conditions are shown in Table 5. The conditions are set conservatively with taking the grain growth for the item 1) and Mn compounds for the item 2) into considerations among the five items of metallographic structural changes which may occur for the material as followings.

1) Grain growth for strengthening
2) Growth of Mn compounds for particle dispersion strengthening
3) Decrease of Mg solid solution strengthening
4) Decrease of work strengthening
5) Growth of particles for precipitation strengthening

In the above considerations, it is confirmed that Mg content is decided in the range without decreasing of solid solution strengthening for the item 3), work strengthening is relieved by the annealing heat treatment for the item 4) and no elements of precipitation strengthening included for the item 5), therefore these strengthening mechanisms are not necessary to be taken into account [3].
After the heat treatment of the materials, tensile tests were conducted at room temperature and elevated temperatures. The tests procedure is according to JIS Z2241 for room temperature and JIS G0567 for elevated temperatures. The test results are shown in Figure 2. The trend curves evaluated for 0.2% proof stress and tensile strength are shown in Figure 3.

Creep Property

The creep strengths are evaluated using the data of A1100-O materials in the public literatures[4],[5],[6], which is more conservative than those of 1B-A3J04-O because any elements to increase the mechanical properties are little included in the A1100 alloy. The data of creep rupture tests for 1B-A3J04-O up to about 2000h are shown in Figure 4 together with the data of A1100-O. For the creep tests, the Materials for mechanical property were used as a conservative condition and the tests procedure is according to JIS Z2271. In this Figure, it is confirmed that the creep strengths of A1100-O is much more conservative than those of 1B-A3J04-O. From the data of A1100-O, the stresses of 100,000h creep rupture and the minimum creep rate of 0.01%/1000h are extrapolated for setting the maximum allowable stress value; S.

Allowable Stress

The allowable stresses in each elevated temperature are evaluated by the trend curve methods, and the evaluating procedure is according to the material code of the Japanese Society of Mechanical Engineers(JSME). The specified strengths of the Material for mechanical property at room temperature with the long-term heat treatment are evaluated with using the same methods for the specified strengths of the initial material described in the above section. The allowable stresses such as Sy and Su at each elevated temperature are evaluated by the specified strengths at room temperature multiplied by the values of the trend curves, and Sm is also evaluated by these tensile properties for Sy and Su. In addition, S is evaluated by using both these tensile properties and the creep properties. The evaluated allowable stresses are shown in Table 6.

6. OTHER PROPERTIES

Fracture Toughness

Generally speaking, aluminum alloy is a ductile material but boron compounds makes fracture toughness lower, therefore the J_{IC} tests were conducted to evaluate whether the unstable fracture will occur or not on the 9m drop test conditions. For this evaluating test, the Standard materials were used to evaluate them as an average condition and the tests procedure is according to ASTM E1820. The tests results are shown in Figure 5. From the test results, though the detailed evaluation is not described here, it is confirmed that the material for the basket of TK-26 transport and storage cask designed by Transnuclear, Ltd. and Kobe Steel, Ltd does not fracture unstably.

Thermal and Elastic Properties

The thermal expansion coefficient, elastic modulus, specific heat, thermal conductivity and Poisson’s ratio in elevated temperatures are shown in Figure 6, 7, 8, 9 and 10, respectively. For these evaluating tests, the Standard materials were used to evaluate them as an average condition. For the thermal expansion coefficient, elastic modulus, specific heat and Poisson’s ratio, there are no significant effect of the long-term heat treatment. On the other hand, for the thermal conductivity, the values with the long-term heat treatment are a little larger than those without it. It is estimated that a small amount of supersaturated Mn in the material precipitates during the long-term heat treatment.

7. CONCLUSION

Kobe Steel, Ltd. has developed the new extruded material “1B-A3J04-O”. It is the Al-Mn-Mg alloy with about 1% enriched boron. For this material, the mechanical properties and other properties necessary for cask basket design have been evaluated. It is also confirmed that there is few or no effect of the long-term heat treatment under the conservative condition considering the heat history up to 60 years. Using the data of the long-term heat treatment materials, the allowable stresses were evaluated according to the JSME material code.

Table 1 Specification of chemical composition for 1B-A3J04-O (mass%)

Alloy	B	Si	Fe	Cu	Mn	Mg	Zn	Others		Al
								Each	Total	
1B-A3J04-O	0.8 - 1.3	0.25	0.25	0.05	1.2 - 1.4	1.0 - 1.4	0.05	0.05	0.15	Re.
1%B-A3004N-H112 (Former developed material)*	0.8 - 1.3	0.30	0.7	0.40	1.4 - 1.8	1.2 - 1.7	0.25	0.05	0.15	Re.
A3004-H112 (Normal material)*	-	0.30	0.7	0.25	1.0 - 1.5	0.8 - 1.3	0.25	0.05	0.15	Re.

*) For information

Table 2 Chemical analysis results of the specimens (Materials for mechanical properties) (mass%)

Specimen No.	Cross-sectional shape	Si	Fe	Cu	Mn	Mg	Zn	B	Others (Ti)	Al
No.22	Flat bar	0.08	0.09	< 0.01	1.23	1.06	0.01	1.04	0.02	Re.
No.24		0.08	0.09	< 0.01	1.21	1.03	< 0.01	1.03	0.02	Re.
No.26		0.08	0.09	< 0.01	1.25	1.06	0.01	1.04	0.02	Re.
No.20	Hollow	0.08	0.09	< 0.01	1.23	1.00	0.01	1.07	0.02	Re.
No.28		0.09	0.09	< 0.01	1.22	0.99	< 0.01	0.99	0.02	Re.
No.30		0.08	0.09	< 0.01	1.22	1.05	0.01	1.06	0.02	Re.

Table 3 Chemical analysis results of the specimens (Standard materials) (mass%)

Specimen No.	Cross-sectional shape	Si	Fe	Cu	Mn	Mg	Zn	B	Others (Ti)	Al
No.32	Flat bar	0.16	0.15	< 0.01	1.38	1.26	0.01	1.06	0.02	Re.
No.34		0.16	0.15	< 0.01	1.37	1.20	0.01	1.07	0.01	Re.
No.36	Hollow	0.17	0.16	< 0.01	1.36	1.20	0.01	1.10	0.02	Re.

Table 4 Specified strength at room temperature of no-aging material

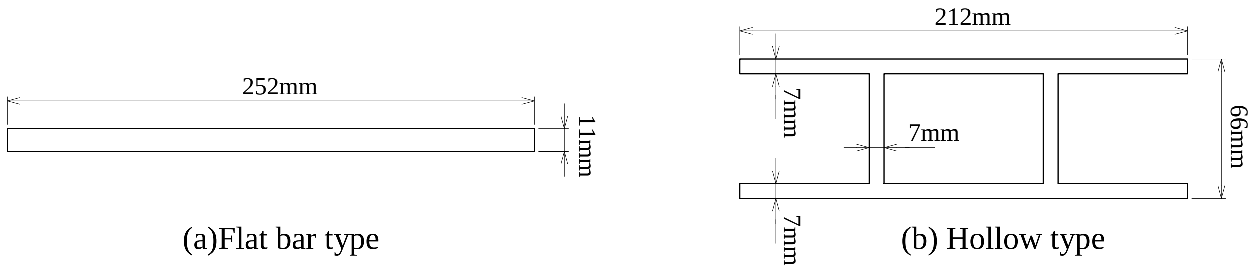
	Average	Standard deviation	Tensile properties including 99% reliability	Specified strength of initial material at room temperature
Tensile strength (MPa)	171.3	6.97	155.1	≥ 155
Proof strength (MPa)	80.8	4.52	70.3	≥ 70
Elongation (%)	22.8	2.81	16.3	≥ 10

Table 5 Conditions of long-term heat treatment

Specimen No.	Flat bar type : No.22, 24, 26 Hollow type : No.20, 28, 30
Temperature (^{o}C)	300
Duration time (h)	1,000

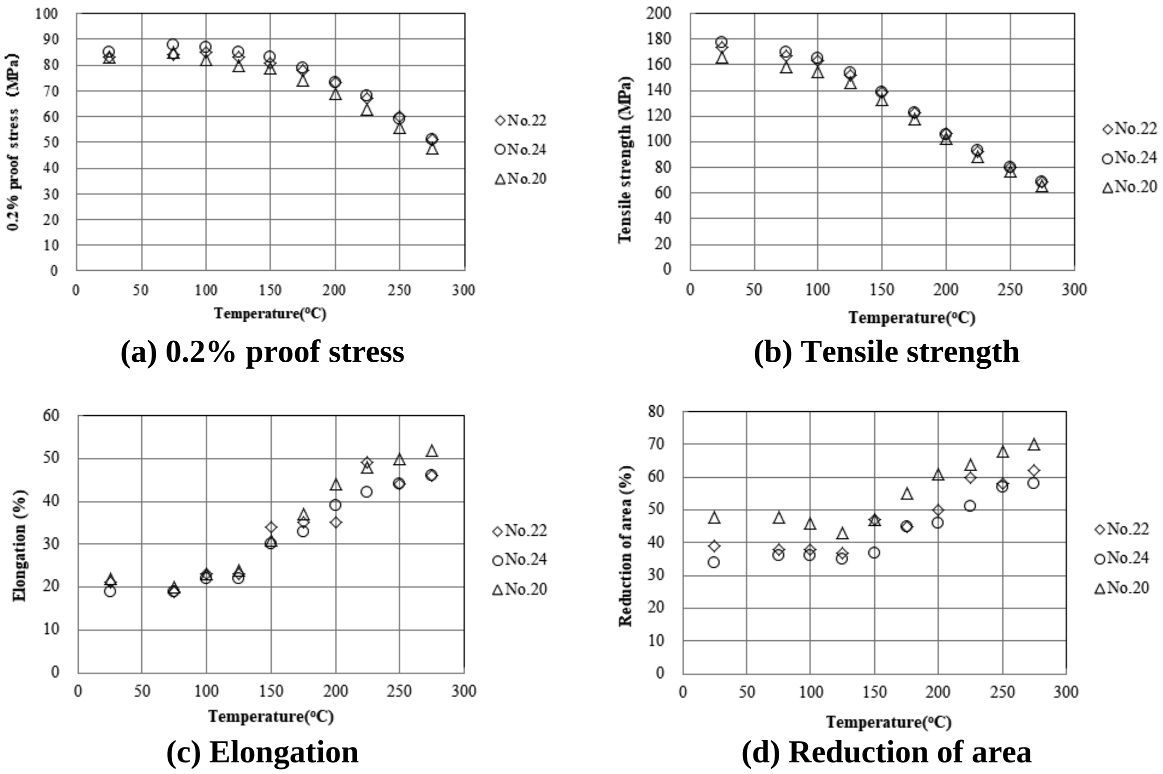
Table 6 Allowable stress of 1B-A3J04N-O

Temperature (^{o}C)	-40～40	75	100	125	150	175	200	225	250
Yield strength value : Sy **(MPa)**	66	66	66	65	63	60	56	51	45
Tensile strength value : Su **(MPa)**	155	149	144	135	123	109	94	81	70
Design stress intensity : Sm **(MPa)**	44	44	44	43	42	40	34	29	25
Maxim allowable stress value : S **(MPa)**	44	44	44	42	12	8.7	6.7	5.4	4.1



(a)Flat bar type (b) Hollow type

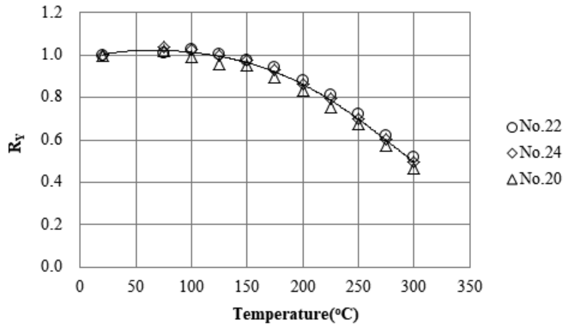
Figure 1 Cross-sectional shapes of specimens



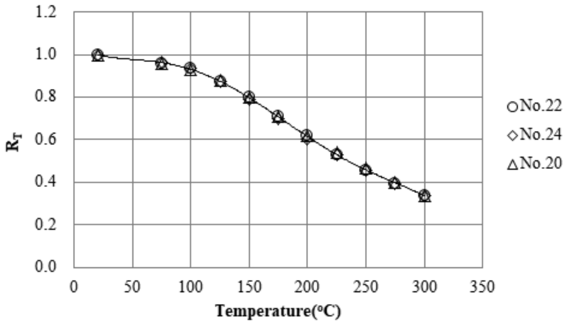
(a) 0.2% proof stress **(b) Tensile strength**

(c) Elongation **(d) Reduction of area**

Figure 2 Tensile strength at elevated temperature

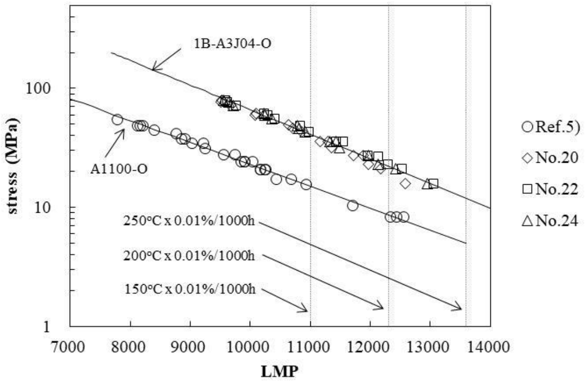


(a) 0.2% proof strength



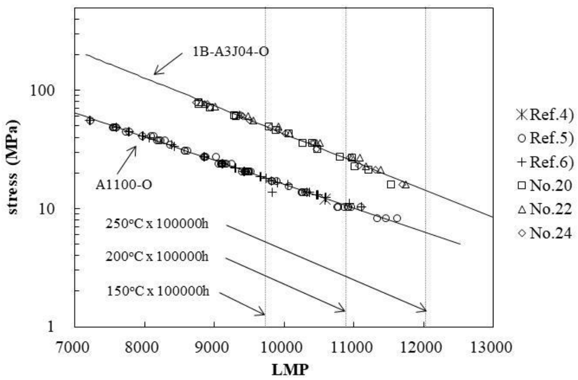
(b) Tensile strength

Figure 3 Trend curve



$$\mathrm{LMP} = (\mathrm{T} + 273.15) \times (19 - \log \dot{\varepsilon})$$

(a) Minimum creep rate property



$$\mathrm{LMP} = (\mathrm{T} + 273.15) \times (18 + \log tr)$$

(b) Creep rupture property

Figure 4 Results of creep tests

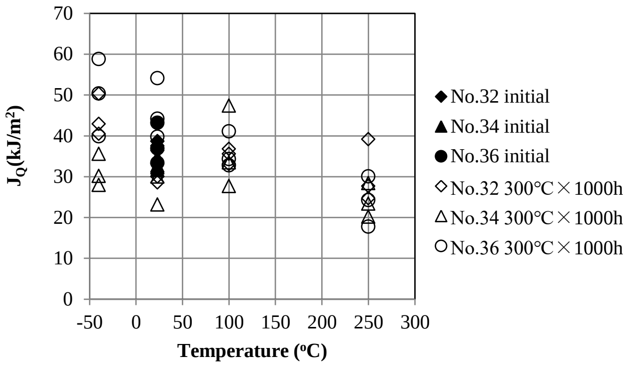


Figure 5 Fracture toughness J_{IC} in elevated temperature

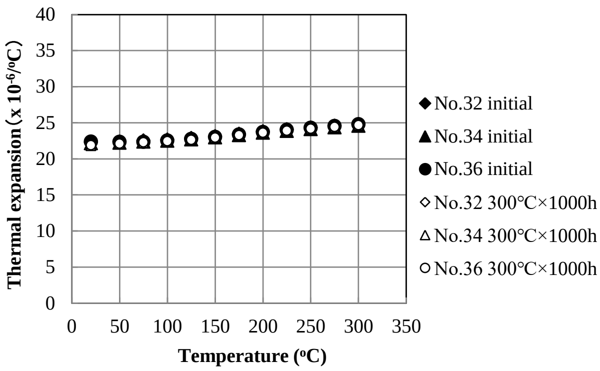


Figure 6 Thermal expansion coefficient in elevated temperature

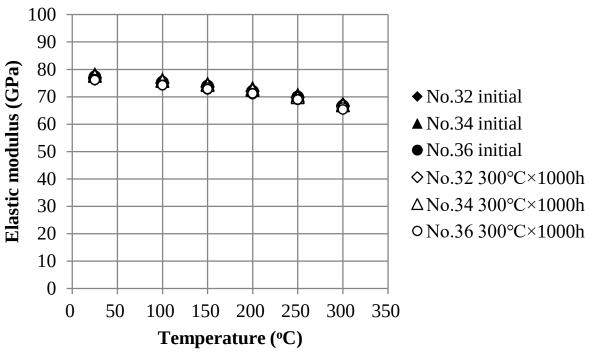


Figure 7 Elastic modulus in elevated temperature

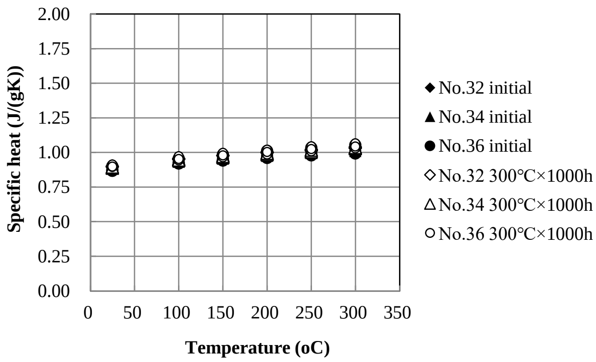


Figure 8 Specific heat in elevated temperature

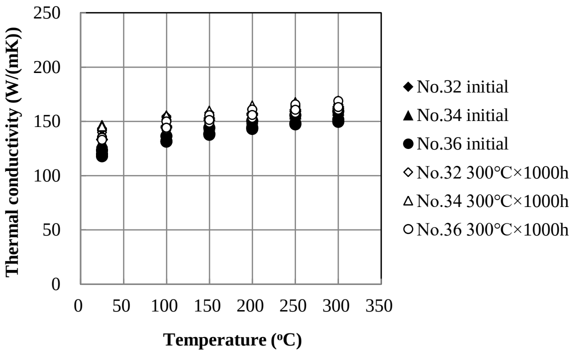


Figure 9 Thermal conductivity in elevated temperature

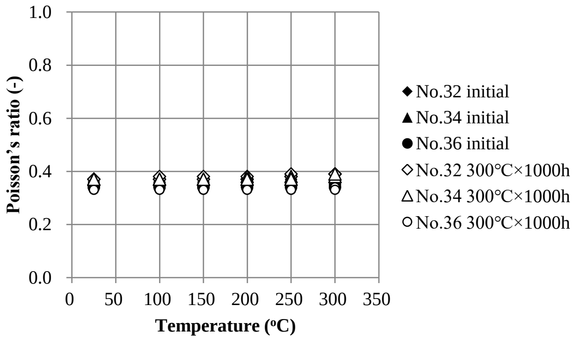


Figure 10 Poisson's ratio in elevated temperature

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