Estimation Formula of the Variation in Mechanical Strength of Borated Aluminum Alloys

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INTRODUCTION

Among the properties, such as thermal, containment, shielding, and criticality properties, which are required for spent-fuel casks for transport and/or storage, it is the thermal and criticality properties that play a very important role for the baskets that hold spent-fuel assemblies. The use of aluminum alloys for baskets offers significant advantages in thermal conduction and light weight. Furthermore, if aluminum alloys that contain boron are used, there is the merit of criticality. Thus, borated aluminum alloys are one of the materials suitable for baskets. In addition, baskets may need to be evaluated for structural strength because baskets must demonstrate safety-related properties in order to hold spent-fuel assemblies. For this reason, it is necessary to design baskets with material strength in mind.

The borated aluminum alloy that has been adopted for such baskets at Kobe Steel Ltd. is a precipitation hardening aluminum alloy (6000 series) which contains some boron. In general, it is known that the material strength of precipitation hardening aluminum alloys decreases with overaging. That is, the material strength of 6000 series aluminum alloy decreases with the growth of Mg_2Si precipitates.

It is therefore necessary to design baskets taking into account the deterioration of material strength caused by overaging during the period of use.

ESTIMATING FORMULA

An estimation formula has been developed to predict the level of deterioration of material strength caused by overaging and verify it by experiments that simulate a basket-temperature decrease.

The formula is based on the following Equation (1), known as Ashby's Equation (Kelly and Nichlson 1971):

$$\sigma = \sigma_0 + CG\ (b\gamma / \lambda)^{1/2} \qquad (1)$$

where σ_0 = matrix strength

C = constant

G = shear modulus

b = burgers vector

γ = strain, and

λ = average distance between particles on slip plane.

The first term of Equation (1) expresses with matrix strength without Mg_2Si precipitation hardening, while the second term of Equation (1) expresses strength with Mg_2Si precipitation hardening.

When Mg_2Si precipitations grow vertically from each other, the $(1/\lambda)$ of the second term of Equation (1) is shown by the following Equation (2) (Kouda1976):

$$1/\lambda = (NL/\sqrt{3})^{1/2} \tag{2}$$

where N = number of Mg_2Si precipitates per unit volume, and

L = average length of Mg_2Si precipitates.

EXPERIMENT

Specimens of borated aluminum alloy that had been heat-treated as T6 were left at temperatures that simulate a decrease in the basket temperature. The specimens were taken out after 100, 300, 1,000, 3,000, and 10,000 hours, and tension tests were carried out at the temperature on emerging. The pattern of the decrease in basket temperature is shown in Fig. 1.

TEM observation was carried out for tested specimens. The number of precipitates per unit volume (N) and length of precipitates (L) were measured, with the results shown in Table 1. Fig. 2 shows the images of the Mg_2Si precipitations.The figure clearly demonstrates how Mg_2Si precipitates grow in the direction of <001> against an aluminum matrix. This is in good agreement with the conditions referred to in Equation (2).

In addition, matrix strength (σ_0) was measured, at 300, 323, 373, 423, 523, and 573K, making use of the specimens whose chemical compositions as same as borated aluminum alloy minus Si, Mg, and B. The results are shown in Fig. 3.

CONSIDERATION

The formula for estimation of variation in mechanical strength is based on the following Equation(3) that combines Equations(1) and (2):

$$\sigma = \sigma_0 + CG(b\gamma \sqrt{NL/\sqrt{3}})^{1/2} \tag{3}$$

Next, the growth of the Mg_2Si precipitates was considered according to Ostwald growth with the following assumptions concerning the precipitates:
①The average cross-sectional area is proportional to the second power of the length.
②As for the length, Ostwald growth (third power rules) is materialized as follows:

$$L^3 - L_0{}^3 = \int_0^t k(T(t))dt \tag{4}$$

where T(t) = temperature (time dependence), and
k = a value which does not change for a fixed temperature.

Fig. 4 shows the growth of the Mg_2Si precipitates. The intercept of the axis by the ordinate expresses the value of $L_0{}^3$, while the gradient expresses the value of k. The values of $L_0{}^3$ and k are shown in Fig. 4.

The value of k is expressed as a function of temperature:

$$k = P/T \exp(-Q/T) \tag{5}$$

where P = a constant value (temperature independence)
Q = activation energy for lattice diffusion of Mg in Al
= 140 kJ / mol (Meherer 1990).

When the value of k shown in Fig. 4 is used, the constant (P) can be calculated to be 2.44×10^{12} at maximum attaining temperature presented as 503K.

The first term of Equation (3), σ_0, is shown as a function of temperature(see Fig. 3), while the relation between temperature (T) and time (t) is shown in Fig. 1. With these, the variation of σ_0 that takes place when basket temperature decreases can be calculated. Consequently, in cases when the variation of NL in the second term of Equation (3) is known, the variation in the mechanical strength of borated aluminum alloys can be predicted.

Concerning the value of NL, the following Equation (6) is prescribed with the condition that the volume fraction of Mg_2Si precipitates is constant:

$$N \cdot L \cdot S = V_f \tag{6}$$

where S = average cross-sectional area of Mg_2Si precipitates ($S = \alpha L^2$).

Hence,

$$N \cdot L = V_f / (\alpha L^2) = \beta / L^2 \tag{7}$$

where β = constant.

The variation with NL in a decrease in basket temperature is shown in Fig. 5.

Thus, Equation (3) can be expressed as a function of time. Here, the values, C = 0.4 (constant), G = 26100MPa (Nihon Kinzoku Gakkai 1993), b = 0.285nm and γ = 0.029 (uniform elongation) are put into Equation (3). Fig. 6 shows the variation in tensile strength of borated aluminum alloys with a decrease in basket temperature.

Matrix strength increases as temperature decreases over time. On the other hand, precipitation hardening strength decreases with the growth of Mg_2Si precipitates until approximately 3,000 hours, then levels off. As a result, the tensile strength of borated aluminum alloys can be expressed as the sum of matrix strength and precipitation hardening strength. As shown in Fig. 6, there is a good coincidence between calculated values and measured values.

SUMMARY AND CONCLUSION

The tensile strength of borated aluminum alloys is determined by matrix strength and precipitation hardening strength. The lower the temperature, the higher the matrix strength, while the greater the overaging, the lower the precipitation hardening strength. It can be understood by use of the estimation formula that these two effects will finally balance each other out.

In conclusion, the estimation formula may be applied to predict the continuous variation in material strength not only for precipitation hardening aluminum alloys but also for precipitation hardening-type metals. Therefore, design of materials and equipment, as well as demonstration tests, will be shortened and rationalized by using the estimation formula for materials whose strength may decrease with over-aging.

REFERENCES

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Table 1 Value of NL

t (hour)	N ($1/\mu m^3$)	L (μm)	NL($1/\mu m^2$) measured	NL($1/\mu m^2$) calculation
5	9863	0.28	2762	122
100	855	0.285	244	118
300	357	0.293	105	111
1000	310	0.316	98	96
3000	197	0.357	70	75
10000	165	0.4	66	60

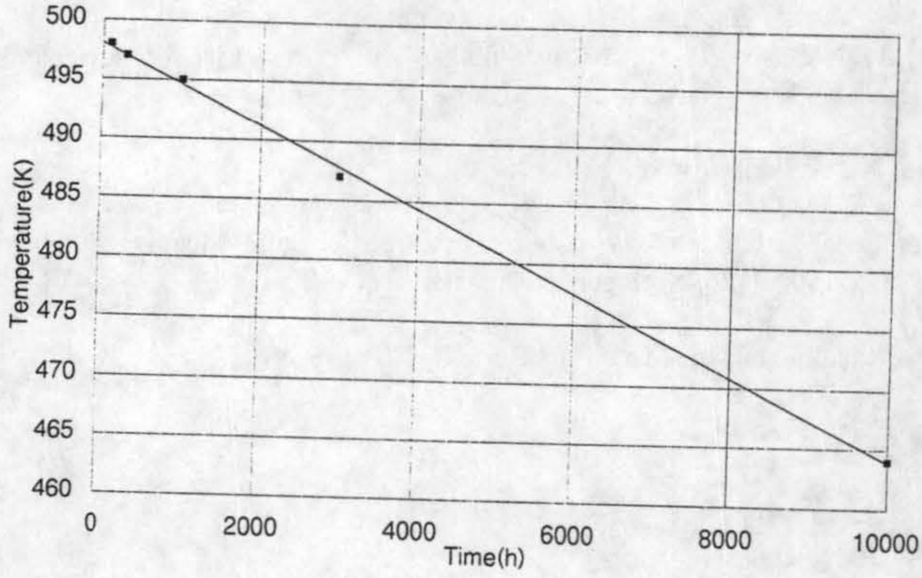

Fig.1 Pattern of basket temperature decrease

Fig.2 TEM micrographs of Mg_2Si precipitates after 100 hours

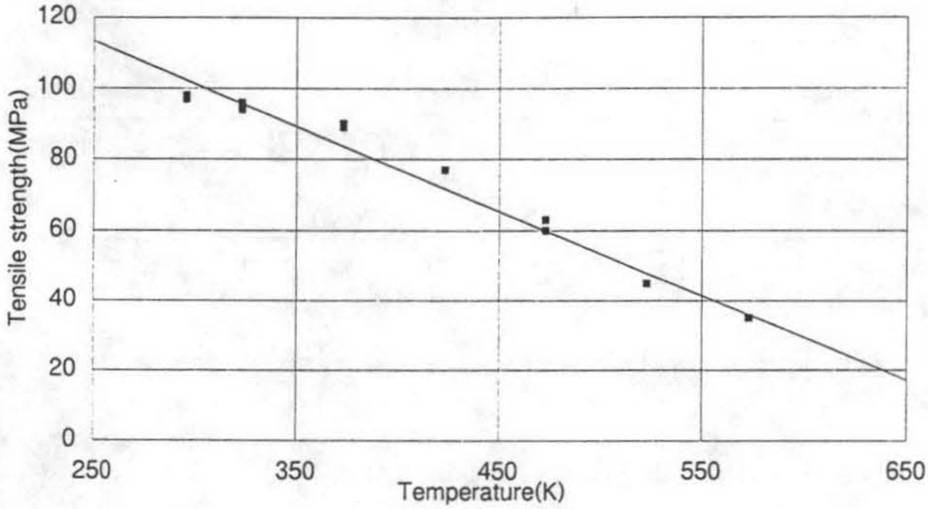

Fig.3 Temperature dependence of matrix strength (300K, 323K, 373K, 423K, 523K, 573K)

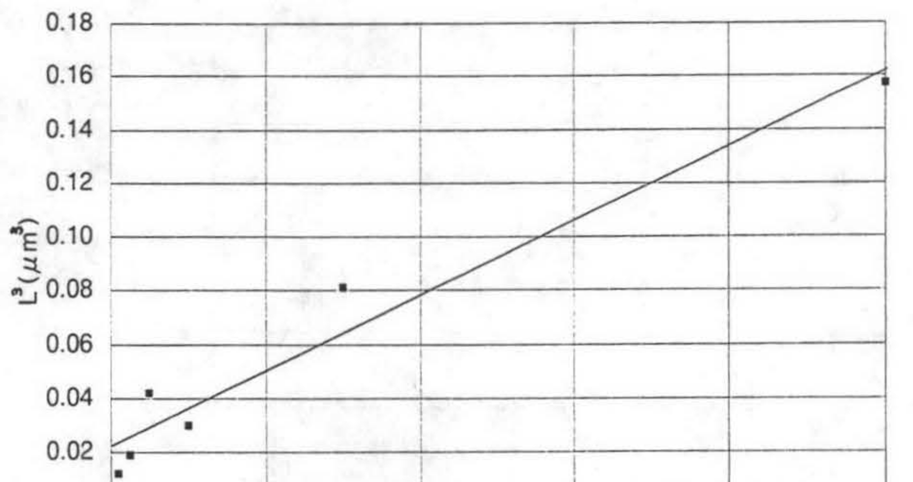

Fig.4 Growth of Mg_2Si precipitates at 503K

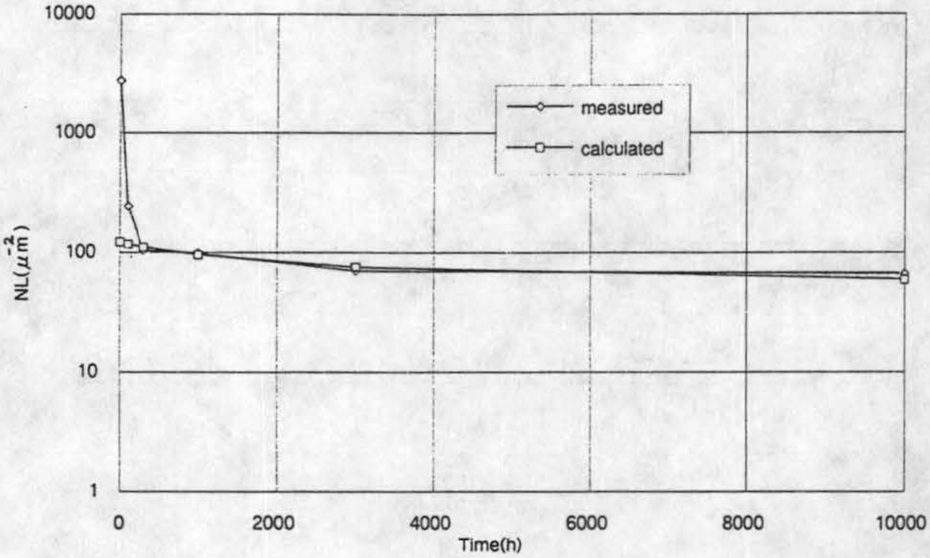

Fig.5 Variation in NL with a decrease in basket temperature

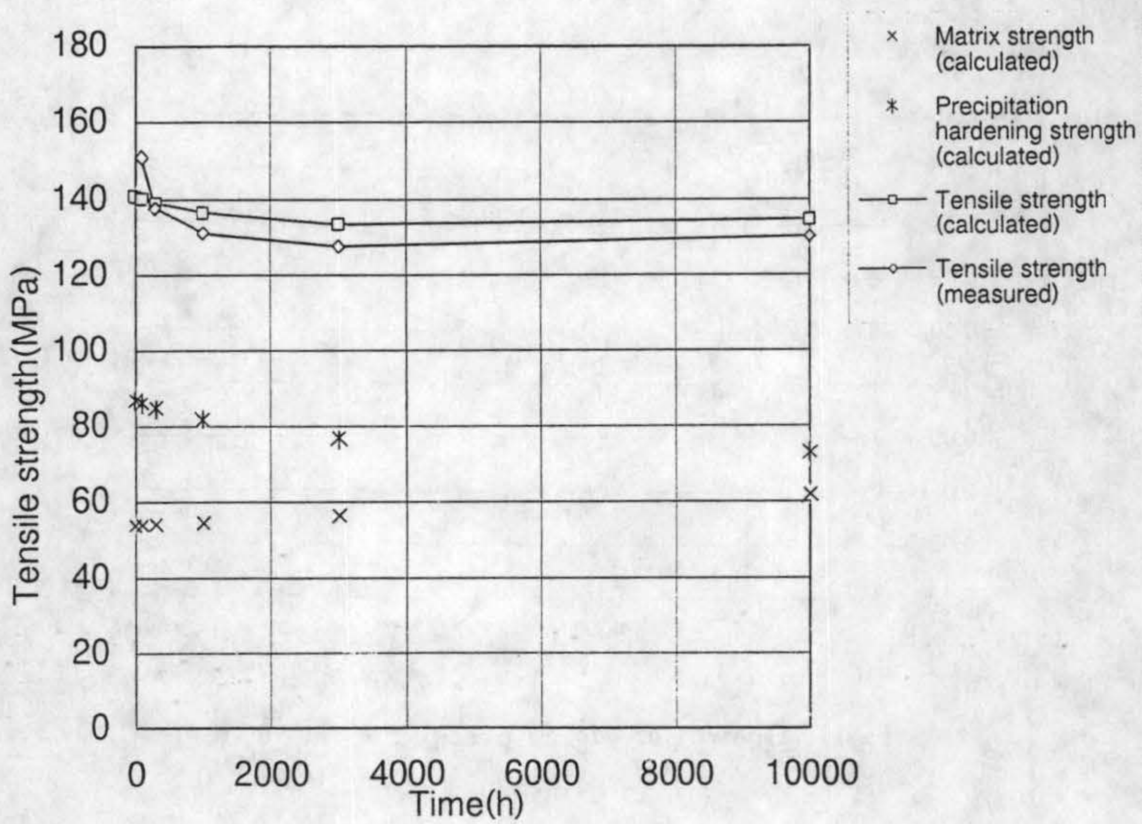

Fig.6 Results for tensile strength of borated aluminum alloy (calculated vs. measured)