Technology for Predicting Residual Stress in Extruded Members of 7000 Series Aluminum Alloy Considering Heat Treatment Process

Hiroaki HOSOI*[1]

*[1] Application Technology Center, Technical Development Group

Abstract

Extruded members of 7000 series aluminum alloy, which has the highest 0.2% proof stress among aluminum alloys, is effective for automotive weight reduction. However, its high sensitivity to stress corrosion cracking (SCC) makes it important to manage residual tensile stress in the members. This paper describes an equation to predict residual stress after artificial aging treatment or after the paint baking process from the residual stress caused by plastic forming during T1 tempering of 7000 series aluminum alloy on the basis of the creep test results of 2 types of newly developed alloys and an extruded material made of standard 7003 alloy. It has been clarified that the artificial aging and paint baking process for extruded members of 7000 series alloy significantly reduce the tensile residual stress caused by plastic forming during the T1 tempering, reducing the risk of SCC.

Introduction

The development of technologies to control CO_2 emissions from automobiles is accelerating worldwide. The weight reduction of structural members is the most basic and effective solution, and Kobe Steel, which has a diverse business and product menu, including steel, aluminum, and welding materials, is also contributing in this area. In particular, for structural members such as bumper reinforcements, side door reinforcements, and side sills, aluminum alloy extruded profiles with hollow cross-sections and high degrees of design freedom can be used, enabling significant weight reduction in comparison to conventional structures combining steel sheets. For these members, Kobe Steel has proposed extruded members made of 7000 series aluminum alloy (hereinafter referred to as "7000 series alloy"), which is expected to have a strength and weight reduction effect exceeding those of 6000 series aluminum alloy (hereinafter referred to as 6000 series alloy), which has been generally used as a structural material. These 7000 series alloy members have been adopted in many automobiles, mainly in the middle-to-high price range.[1)-3)]

The 7000 series alloys, which are Al-Zn-Mg based, have 0.2% proof stress that is exceptionally high compared with those of other alloy systems, but have a susceptibility to stress corrosion cracking (hereinafter referred to as "SCC"), in which the higher the alloy's strength, the greater the susceptibility tends to become.[4)] There are various theories about the occurrence mechanism of SCC, such as the hydrogen embrittlement theory and the anode melting theory, and research is still underway in search of elucidation. From the phenomenal aspect, however, SCC is known to occur when an alloy with high SCC susceptibility is exposed to a corrosive environment under high tensile stress for longer than a specific period. Therefore, when 7000 series alloy is applied to members exposed to corrosive environments, the non-occurrence of SCC must be ensured, and it is essential to manage its cause, i.e., tensile stress. Tensile stresses are roughly classified as tensile stress that resides in the member (residual tensile stress), tensile stress caused by static self-weight, and tensile stress occurring inside a member, caused by various inertial forces during running and road surface input. Of these, the tensile stress caused by the self-weight is generally negligible, and the tensile stress that occurs during driving also has a short loading time, so they are unlikely to be the factors causing SCC. In other words, the stress that requires the most control is the residual tensile stress in each member.

The residual tensile stress in an extruded member of 7000 series alloy mainly occurs during plastic working. The residual tensile stress is relaxed during heat treatment, such as artificial aging in the manufacturing process and the paint baking process at automobile manufacturers, and the residual tensile stress may have decreased by the time of market shipment. This stress relaxation proceeds as creep deformation with the residual stress as the driving force, accompanied by a decrease in elastic strain. The stress relaxation rate depends on stress and temperature and is also considered to depend on dislocation density, i.e., pre-strain. Therefore, a method is required for predicting residual stress after heat treatment, such as artificial aging processing and paint baking, from the residual stress generated by plastic working. In this study, creep testing has been performed by changing the applied stress and pre-strain at temperatures that assume the artificial aging and paint baking for the extruded material of Kobe Steel's newly developed 7000 series alloys and the standard 7003 alloy. The obtained creep characteristics have been converted into stress relaxation characteristics, which has led to the development of a method using the residual tensile stress after artificial aging and paint baking from the initial residual tensile stress.

1. Manufacturing process of extruded member made of 7000 series alloy for automobiles

Fig. 1 shows a typical manufacturing process for extruded automobile members, such as bumper reinforcements, side door reinforcements, and side sills, made of 7000 series alloy. Fig. 1 separately depicts the process of manufacturing the members in an extrusion factory and the manufacturing process in an automobile factory.

The extrusion factory performs billet casting, homogenization heat treatment, hot extrusion, cooling, and tension straightening to ensure straightness, followed by cutting to the member to its specified length. In the tension-straightening process, a plastic strain of approximately 0.01 is usually applied almost uniformly when cold, and it is considered that the residual stress generated in the cooling process almost disappears in this tension straightening. Subsequently, the bumper reinforcement members and the side-door reinforcement members are subjected to plastic working such as bending and hemming under T1 tempering, which offers superior workability. In the bending process, the cross-sectional shape is kept almost constant. When spring back occurs after the plastic deformation, residual tensile stress up to 0.3 to 0.7 times the 0.2% proof stress occurs in the longitudinal direction in the region from the neutral axis of bending to the outside (tension side) of the bending. In the hemming process, a load in the direction orthogonal to the longitudinal direction is applied to an end of the extruded member, deforming the cross-section. Of the sides that make up the cross-section, the side almost parallel to the direction of load application is subjected to great bending deformation. Due to this bending deformation, residual tensile stress of approximately 0.5 times the 0.2% proof stress occurs on the inner surface of the bending on the compressive deformation side in the direction orthogonal to the longitudinal direction. Subsequently, artificial aging is applied to achieve the specified mechanical properties. In the case of the artificial aging of 7000 series alloy, 2-step aging[5] may be performed, and the 2nd stage aging, whose temperature is higher, generally involves 3 to 24 hrs. of processing time in the temperature range from 115℃ to 180℃.[6] Finally, machining such as drilling and cutting is performed, and the product is shipped to automobile factories.

In an automobile factory, various mechanical joining methods, such as self-piercing rivets (SPR), are used, in addition to bolt fastening and arc welding, to assemble skeletons, and subsequently, followed by paint baking. Skeleton members, such as side-door reinforcement members, are attached to the skeleton, pass through the paint baking process, and are subjected to the thermal effect. On the other hand, so-called hang-on parts such as bumper reinforcement members are not affected by the heat of the paint baking process because they are attached to the skeleton, which has passed through the paint baking process. The paint baking is divided into a pretreatment process, an electrodeposition process, a washing process, and a drying process. The final drying process uses a high-temperature drying furnace to bake steel sheets, aluminum alloy sheets, sealers, and the like with bake hardenability in addition to the electrodeposition paint. The thermal history of each member is considered to differ significantly since the temperature and time spent in the drying furnace depends on the automobile manufacturer, and the temperature differences among the sites are not negligible. However, even in a steel sheet with a large heat capacity, the temperature of which is the most difficult to raise, the temperature is generally maintained for at least 20 min after reaching 170℃.[7]

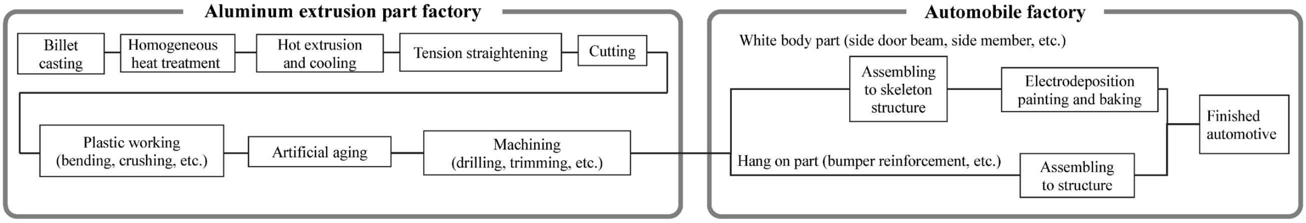


Fig. 1 Typical manufacturing process of 7000 series aluminum alloy extrusion parts for automobiles

2. Creep testing

2.1 Testing conditions

Three types of alloys were selected: Kobe Steel's newly developed alloy A, newly developed alloy B,[2), 3)] and 7003 alloy, a standard alloy selected as a material for comparison. The newly developed alloy A and 7003 alloy are often T5 tempered for use, and the newly developed alloy B is often used after being T7 tempered. **Table 1** summarizes typical mechanical properties in the direction parallel to the extrusion. Hot extrusion was performed using a hydraulic press to produce T1 tempered flat bars, each with a width of 110 mm and a thickness of approximately 3 mm. Then, creep testing pieces with the dimensions shown in **Fig. 2** were collected in the orthogonal direction of the extrusion.

Table 2 summarizes the conditions for the creep testing. Each creep test was carried out at a temperature assuming artificial aging or a paint baking process. In the creep testing assuming artificial aging, all alloys were T1 tempered before testing. The testing temperature assumed T5 tempering for the newly developed alloy A, T7 tempering for the newly developed alloy B, and T5 tempering for the 7003 alloy. The applied stress was changed from 90 MPa to 250 MPa. The testing time was set at 24 hrs. or less, considering the artificial aging time. Testing conditions were added to investigate the effect of pre-strain on the creep strain rate; that is, the newly developed alloys A and B were pre-strained by an applied stress of 220 MPa, and the 7003 alloy was pre-strained by an applied stress of 150 MPa. After machining each creep testing piece, a nominal strain of 0.005 to 0.1 was given while cold, as a pre-strain to the parallel portion, 30 mm long, of the testing piece by a tensile testing machine. The applied stress and creep strain for the pre-strained conditions accounted for the reduction of the cross-sectional area and changes in the gauge length.

Table 1 Typical mechanical properties in longitudinal direction

Alloy and temper	Tensile strength (MPa)	0.2% proof stress (MPa)	Elongation (%)	Note
Alloy A-T5	400	350	15	Kobe Steel, Ltd. developed alloy
Alloy B-T7	440	400	14	
7003-T5	315	255	15	Standard alloy

Typical value
Longitudinal direction

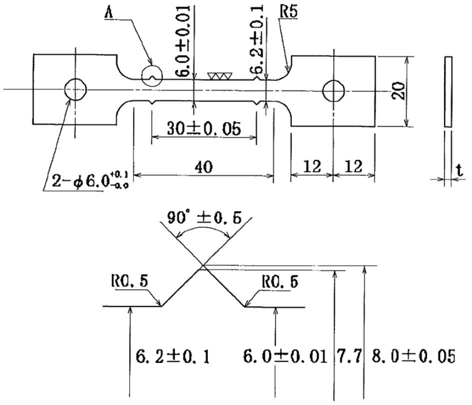


Fig. 2 Dimensions of creep testing pieces

For creep testing under the temperature conditions assuming the paint baking process, the newly developed alloy A was subjected to T5 tempering, the newly developed alloy B was subjected to T7 tempering, and the 7003 alloy was subjected to T5 tempering for the artificial aging before the testing. The testing temperature was 170℃, considered the lower limit of the paint baking process, and the applied stress was changed from 60 MPa to 210 MPa. In order to obtain accurate data of steady-state creep under the conditions of minor creep strain and low applied stress, the testing time is set longer than the time for passing through the drying furnace, with a maximum of 4 hrs. The pre-strained conditions were omitted.

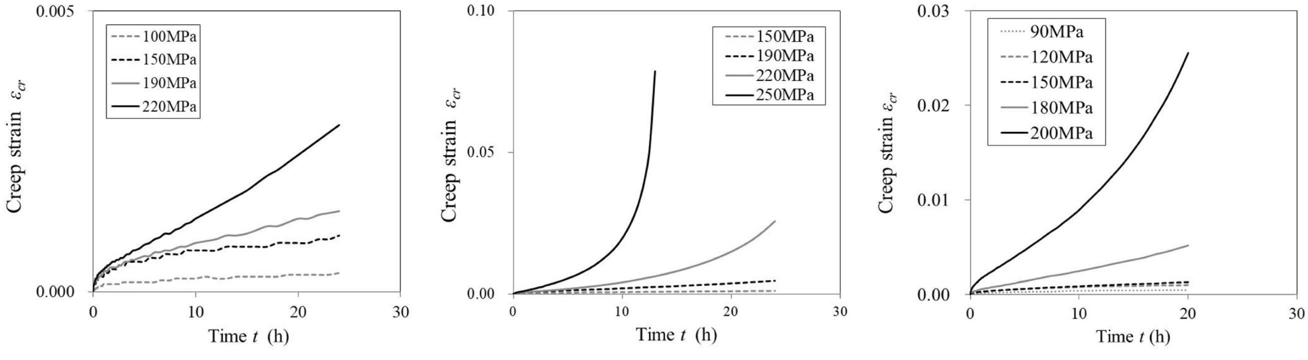
The creep testing method followed JIS Z2271 and included measuring the temporal change of creep strain, in which the elastic deformation is excluded from the total strain.

Table 2 Creep testing conditions

	Creep test 1 (artificial aging process)				Creep test 2 (paint baking process)			
Alloy	Temper of test pieces	Temperature	Applied stress (MPa)	Note	Temper of test pieces	Temperature (℃)	Applied stress (MPa)	Note
Alloy A	T1	Artificial aging temperature for T5	100, 150, 190, 220	Pre-strain 0.01, 0.02, 0.05, 0.1 conditions are added in 220 MPa.	T5	170	60, 90, 120, 150, 180	-
Alloy B	T1	Artificial aging temperature for T7	150, 190, 220, 250	Pre-strain 0.01, 0.02,0.05, 0.1 conditions are added in 220 MPa.	T7	170	60, 90, 120, 150, 180	-
7003	T1	Artificial aging temperature for T5	90, 120, 150, 180, 200	Pre-strain 0.005, 0.01, 0.03, 0.05 conditions are added in 150 MPa.	T5	170	120, 150, 180, 200, 210	-

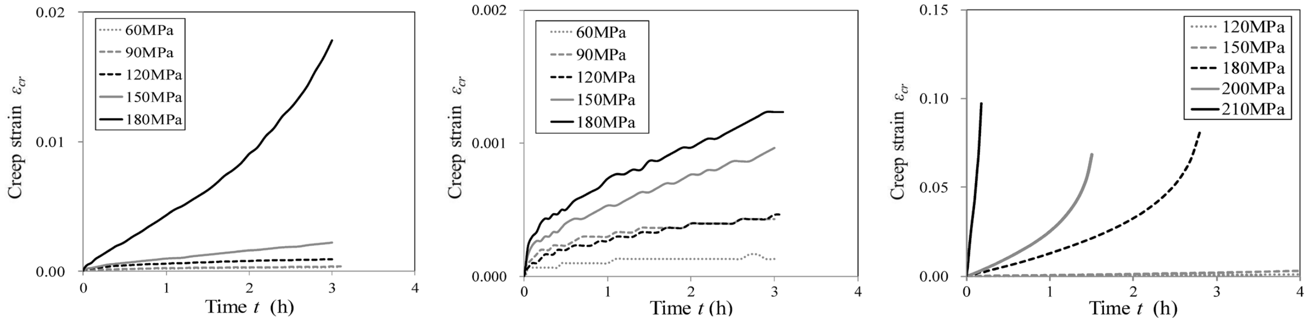
2.2 Testing results

Fig. 3 shows the temporal change of creep strain for each alloy with zero pre-strain at the respective artificial aging temperatures. **Fig. 4** shows the temporal change of creep strain at the temperature assuming the paint baking process. Under all creep testing conditions, the higher the applied stress, the greater the initial transient creep (primary creep) and the greater the slope of the steady-state creep (secondary creep). Accelerated creep has been confirmed under high applied stress, and some conditions have led to breakage. The creep rates for given applied stress cannot be compared due to the temperature difference in the artificial aging conditions; however, at the temperature assuming the paint tempering process shown in Fig. 4, the rate becomes the highest for 7003-T5, followed by T5



(a) Alloy A -T1 (T5 aging temperature) (b) Alloy B- T1 (T7 aging temperature) (c) 7003-T1 (T5 aging temperature)

Fig. 3 Creep strain - time relationships at each alloy's artificial aging temperatures in which pre-strain is not applied (Alloy A: artificial aging temperature for T5, Alloy B: artificial aging temperature for T7, 7003: artificial aging temperature for T5)



(a) Alloy A-T5 (b) Alloy B-T7 (c) 7003-T5

Fig. 4 Creep strain-time relationships at 170℃, which is estimated to be the temperature of the paint baking process (zero pre-strain conditions)

Table 3 Steady state creep rate $\dot{\varepsilon}_{st}$ for each condition (Unit: h^{-1})

(a) Artificial aging temperature

Alloy and temper	Temperature	Applied stress (MPa)								
		90	100	120	150	180	190	200	220	250
Alloy A-T1	Artificial aging temperarture for T5		7.66E-06		1.86E-05		4.33E-05		1.03E-04	
Alloy B-T1	Artificial aging temperature for T7				3.24E-05		1.42E-04		3.14E-04	1.01E-03
7003-T1	Artificial aging temperature for T5	4.00E-05		6.26E-05	6.66E-05	2.08E-04		7.45E-04		

(b) Paint baking temperature (170°C)

Alloy and temper	Temperature (℃)	Applied stress (MPa)						
		60	90	120	150	180	200	210
Alloy A-T5	170	5.45E-05	5.91E-05	1.67E-04	6.20E-04	4.62E-03		
Alloy B-T7		1.08E-05	6.02E-05	8.54E-05	2.11E-04	2.67E-04		
7003-T5				1.08E-04	9.14E-04	1.18E-02	2.43E-02	4.18E-01

Table 4 Steady state creep rate $\dot{\varepsilon}_{st}$ for each pre-strain at artificial aging temperature (A zero value for pre-strain results in no dimension, $\dot{\varepsilon}_{st}$ 0)

Alloy and temper	Temperature	Applied stress (MPa)	Pre-strain						
			0	0.005	0.01	0.02	0.03	0.05	0.1
Alloy A-T1	Artificial aging temperature for T5	220	1.00		2.40	2.98		4.19	4.75
Alloy B-T1	Artificial aging temperature for T7		1.00		1.19	1.94		2.93	3.05
7003-T1	Artificial aging temperature for T5	150	1.00	0.75	1.57		1.92	2.10	

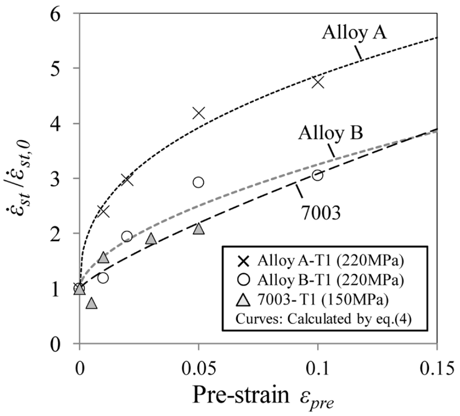


Fig. 5 Effect of pre-strain on steady state creep rate at artificial aging temperature

tempering of the newly developed alloy A and T7 tempering of the newly developed alloy B, in that order. **Table 3** summarizes the results of extracting the steady-state creep area from the creep strain-time relationship and determining the steady–state creep rate, $\dot{\varepsilon}_{st}$.

Table 4 shows the steady-state creep rate under a different pre-strain at each artificial aging temperature. In Table 4, the steady-state creep rate was rendered dimensionless under the condition of pre-strain 0. **Fig. 5** shows the effect of pre-strain on the steady-state creep rate. Fig. 5 also includes approximated curves based on the approximation expression, Eq. (4), described later. It has been confirmed that the steady-state creep rate tends to increase almost monotonously as the pre-strain increases. For example, compared with pre-strain 0 as a reference, the steady-state creep rate of the newly developed alloy A is approximately 2.4 times for pre-strain 0.01, approximately 3.0 times for pre-strain 0.02, and approximately 4.8 times for pre-strain 0.1. There is also a tendency of differences depending on the alloy types.

3. Derivation of prediction formula for stress relaxation characteristics

Attempts have been made to derive a prediction formula for the stress relaxation characteristics in artificial aging and paint baking processes using the creep testing results of extrusions of the 7000 series alloy. The following assumptions have been made in the derivation:

(a) The relief of residual stress progresses when the elastic strain is replaced with creep strain, which is unaccompanied by shape change (the sum of elastic strain and creep strain is always constant).

(b) Focus is to be placed on the residual stress in the principal stress direction. Other principal stresses do not affect the relief rate of focused residual stress and should be treated the same way as the uniaxial stress state. The stress relaxation is evaluated independently for each point and each principal stress component. Non-linear stress relaxation may cause an imbalance in internal force, causing macroscopic elastic deformation, but its effect should be ignored.

(c) The residual stress dependence of creep strain rate is expressed by the power law. For safe-side evaluation, only steady-state creep will be considered, and neither transient nor accelerated creep will be considered. The power law's proportional constant will take the pre-strain dependence into account.

(d) The effect of pre-strain on the creep strain rate has no dependence on the applied stress or the temperature. The effect of pre-strain before artificial aging is preserved as is in the paint baking process after artificial aging. The pre-strain takes a value of 0 or greater as the equivalent plasticity strain. The effects of strain ratio and strain route should be ignored.

Since the shape is considered not to change due to the creep, the sum of the creep strain rate $\dot{\varepsilon}_{cr}$ and the elastic-strain change rate $\dot{\varepsilon}_e$ is 0:

$$\dot{\varepsilon}_{cr} + \dot{\varepsilon}_e = 0 \quad \cdots\cdots\cdots\cdots (1)$$

The elastic strain ε_e is given by Eq. (2) on the basis of Young's modulus E and residual stress σ_{res} :

Table 5 Parameter list of equations for predicting stress relaxation characteristics

Alloy	Temper	Temperature	A_0 (h^{-1})	m	k	n
Alloy A	T1	Artificial aging temperature for T5	6.66E+03	3.16	9.81	0.404
	T5	170℃(paint baking process)	1.48E+07	3.84		
Alloy B	T1	Artificial aging temperature for T7	9.47E+12	6.55	8.64	0.583
	T7	170℃(paint baking process)	9.25E+03	2.88		
7003	T1	Artificial aging temperature for T5	6.09E+04	3.23	13.43	0.809
	T5	170℃(paint baking process)	3.76E+32	13.28		

$$\varepsilon_e = \frac{\sigma_{res}}{E} \cdots\cdots \tag{2}$$

The temperature dependence of Young's modulus is not considered, and Young's modulus at room temperature is assumed. The stress dependence of creep strain rate $\dot{\varepsilon}_{cr}$ shall be expressed by the power law of Eq. (3);

$$\dot{\varepsilon}_{cr} = A(\varepsilon_{pre}) \cdot \mathrm{sgn}(\sigma_{res}) \cdot \left(\frac{|\sigma_{res}|}{E}\right)^m \cdots\cdots \tag{3}$$

wherein m is the stress index (exponential). The absolute value symbol $|\sigma_{res}|$ and signum function, sgn, are used for residual stress σ_{res} to enable handling even when the residual stress is in the compressive direction. In Eq. (3), $A(\varepsilon_{pre})$ is a coefficient corresponding to the pre-strain and gives Eq. (4) that easily expresses Fig. 5 with excellent accuracy:

$$A(\varepsilon_{pre}) = A_0 \cdot (1 + k \cdot \varepsilon_{pre}{}^n) \cdots\cdots \tag{4}$$

wherein A_0 is the coefficient when pre-strain ε_{pre} is 0, and k and n are constants that express the pre-strain dependence. A_0 is determined for each alloy and temperature, and k and n are determined for each alloy. Differentiating Eq. (2) by time and assigning the result to Eq. (1) together with Eq. (3) provide a differential equation for σ_{res}. Solving this equation under the initial conditions (t = 0 and $\sigma_{res} = \sigma_{res,\,0}$) derives Eq. (5):

$$\sigma_{res}(t) = \mathrm{sgn}(\sigma_{res,\,0}) \left\{ |\sigma_{res,\,0}|^{1-m} + A_0 \cdot (1 + k \cdot \varepsilon_{pre}{}^n) \cdot \frac{(m-1)}{E^{m-1}} \cdot t \right\}^{1/(1-m)} \cdots\cdots \tag{5}$$

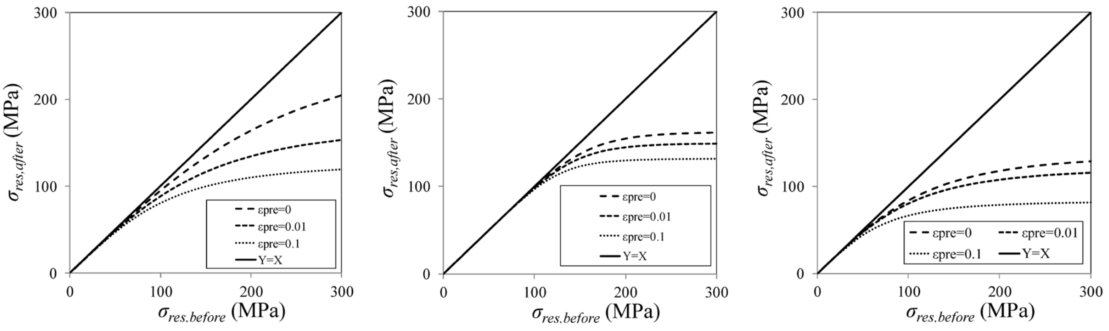
Eq. (5) allows the evaluation of the changes in residual stress caused by the artificial aging and paint baking process. Also, setting the residual stress after artificial aging to the initial value allows the evaluation of residual stress after the artificial aging and paint baking process. **Table 5** summarizes A_0, m, k, and n determined from the experimental results using the least-squares method.

4. Calculation of stress relaxation characteristics

The stress relaxation characteristics have been calculated using Eq. (5) and Table 5. As mentioned above, the artificial aging conditions are T5 treatment standard conditions for the newly developed alloy A, T7 treatment standard conditions for the newly developed alloy B, and T5 treatment standard conditions for the 7003 alloy. The conditions for the subsequent paint baking have all been set to 20 min at 170℃. Young's modulus E has been set to 70 GPa. The pre-strain ε_{pre} has been set to levels, 0, 0.01, and 0.1. **Fig. 6** shows the change in residual stress due to the artificial aging treatment. **Fig. 7** shows the change in residual stress due to the artificial aging treatment and paint baking process. In Fig. 6, the x-axis represents the residual stress before artificial aging, and the y-axis represents the residual stress after artificial aging. In Fig. 7, the x-axis represents the residual stress before artificial aging, and the y-axis represents the residual stress after artificial aging and paint baking. The y-axis value of each curve and the distance in the y-direction from the function y = x correspond to the amount of stress relaxation caused by the heat treatment.

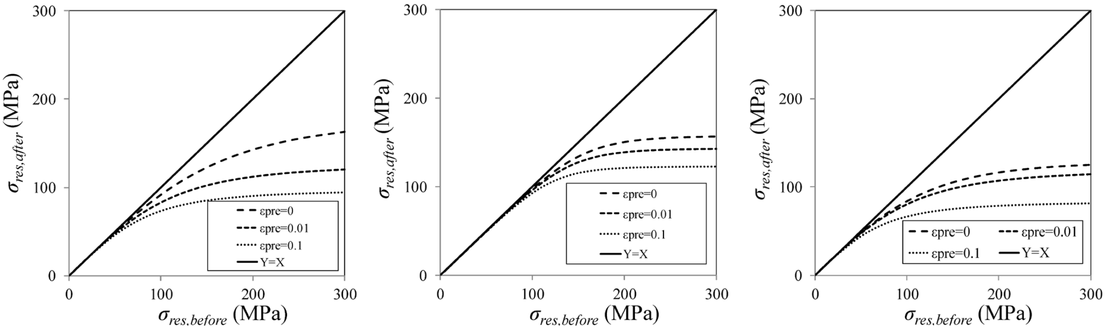
The stress relaxations caused by artificial aging alone and by artificial aging and paint baking tend to be more pronounced as the residual stress and/or pre-strain increase. The residual stress after heat treatment is almost the same as that before the heat treatment when the residual stress before the heat treatment is low but tends to approach a specific value as the residual stress before the heat treatment increases. This tendency is increasingly pronounced in the newly developed alloy B and 7003 alloy. The asymptotic residual stress depends on the pre-strain; the more significant the pre-strain, the lower the value. The comparison between Fig. 6 and Fig. 7 shows that newly developed alloy B and 7003 alloy have significant stress relaxation by artificial aging and little stress relaxation by the paint baking process.

The newly developed alloy A has little stress relaxation due to artificial aging compared with the newly developed alloy B and 7003 alloy.



(a) Alloy A (T5 aging) (b) Alloy B (T7 aging) (c) 7003 (T5 aging)

Fig. 6 Changes in residual stress due to artificial aging process (estimated results using Eq. (5)



(a)Alloy A（T5 aging→170℃×20min） (b) Alloy B（T7 aging→170℃×20min） (c) 7003（T5 aging→170℃×20min）

Fig. 7 Changes in residual stress due to artificial aging treatment and paint baking process (estimate results using equation (5)

Conclusions

The extruded materials of two types of Kobe Steel's newly developed 7000 series alloys and the 7003 alloy, a standard alloy, have been subjected to creep testing simulating the temperature conditions of artificial aging treatment and the paint baking process. The test results have been used to develop a method to predict the residual stress after artificial aging treatment and paint baking process from the initial residual stress generated by plastic working during T1 tempering.

(1) Regarding the newly developed alloy A, newly developed alloy B, and 7003 alloy, data have been obtained for the dependence of the creep strain rate on the applied stress and pre-strain under the temperature conditions assuming artificial aging treatment and the paint baking process.

(2) Under various assumptions, prediction formulas were created for the stress relaxation characteristics during artificial aging treatment and paint baking. The stress relaxations by artificial aging treatment alone and artificial aging treatment + paint-baking processing are more pronounced when the initial residual stress is higher and the pre-strain is greater, and the residual stress tends to approach a specific value.

(3) The above results show that the heat treatment (artificial aging treatment and paint baking process) performed on the extruded members of 7000 series alloys significantly reduces the residual tensile stress caused by the plastic working during T1 tempering and contributes to the reduction of SCC risk.

Extruded members using the 7000 series alloy, which has the highest class of strength among aluminum alloys, can contribute to the weight reduction of automobiles, and there are high expectations from automobile manufacturers. In order to meet their expectations, Kobe Steel will continue to focus on technological development that supports practical application by its customers.

References

1) Y. Takagi et al. R&D Kobe Steel Engineering Reports. 2019, Vol.69, No.1, pp.6-10.
2) T. Oka et al. R&D Kobe Steel Engineering Reports. 2004, Vol.54, No.3, pp.51-53.
3) T. Shikama et al. R&D Kobe Steel Engineering Reports. 2017, Vol.66, No.2, pp.90-93.
4) M. Hirano et al. Journal of Japan Institute of Light Metals. 1991, Vol.41, No.7, pp.477-484.
5) Japan Light Metal Association: The fundamentals of aluminum materials and industrial technology. 1985, p.169.
6) Japan Aluminum Association: Aluminum Handbook. 6th edition, 2001, p.10.
7) K. Sugisaki. Journal of the Surface Finishing Society of Japan. 2002, Vol.53, No.5, pp.293-298.