Prediction of Leveling Warped Metal Plate by Stress Relief Annealing Process

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ABSTRACT

Creep tests were conducted on 5052 series aluminum alloy at various temperatures (250℃, 300℃, 350℃) to confirm their behavior. Based on the results of these creep tests, a simplified calculation model was created to predict the behavior of warpage before and after annealing. The relationships between C-warpage of plate before and after annealing were calculated. The results of the calculations showed that warpage correction by annealing is effective when the warpage before annealing is significantly large, but it has little effect when the warpage before annealing is too small.

Keywords: annealing, creep, stress relief, residual stress

INTRODUCTION

Some precision components are manufactured from metal plates through machining processes. So, to produce parts with superior dimensional accuracy, it is desirable to minimize the deformation before and after machining. Thus, the important quality of the metal plate used for precision components is low residual stress and minimal warpage.

Metal plates are usually manufactured through rolling processes. So, they have high residual stress. There are various methods for removing residual stress and warpage in metal plates, such as roller leveling using bending deformation, stretchers using tensile deformation, and stress relief annealing using creep deformation. Roller levelers and stretchers are methods to apply mechanical external forces to warped plates to flatten them by plastic deformation, and there have been numerous studies reported on these methods' mechanisms[1, 2]. On the other hand, stress relief annealing is a method to flatten plates by creep deformation at high temperatures. While there have been many studies on the mechanism of creep deformation[3, 4, 5], the study of the process using stress relief annealing has only been reported in the welding field[6]. In particular, there are few studies of stress relief annealing in the field of leveling warpage plates[7].

Some aluminum alloy plates are used as materials for components requiring high dimensional accuracy in semiconductor manufacturing equipment and liquid crystal display manufacturing equipment, with high demands for reducing residual stress and warpage. Roller levelers and stretchers, stress relief annealing are used for correcting aluminum alloy plates. In particular, stress relief annealing is a significantly effective process for the final product's warpage. Stress relief annealing including for the manufacturing processes of 5000 series aluminum alloy plates for precision components is the process of annealing stacked plates with opposing warpage, placing a weight such as an iron or aluminum base plate on top[6]. This method can reduce warpage height from several millimeters to below 0.5mm.

The authors investigated the creep characteristics of 5052 series aluminum alloy and developed a simplified predictive calculation model for correcting plate warpage through stress relief annealing.

TENSILE TESTS AND CREEP TESTS

Test Conditions

Tensile tests and creep tests were conducted on 5052 series aluminum alloy at temperatures of 250, 300, and 350℃. For the tensile tests, specifically, specimens with necks as specified in JIS G 0567:2020 and ISO 6892-2:2018 were subjected to tensile testing at a tensile rate of 1.0mm/min until fracture at temperature of 250℃, 300℃, and 350℃. The creep test conditions were shown in Table 2. Creep test specimens with necks as specified in JIS Z 2271:2010 and ISO 204:2009 were heated at temperature of 250°C, 300°C, and 350°C, and were subjected to continuous tensile loading at stresses of 30%, 45%, 60%, and 75% of the 0.2% yield strength for 8.1 hours. If fracture of these specimens occurred before reaching 8.1 hours, the creep test was concluded at that point.

Test Results

Tensile test results are shown in Figure 1, and creep test results are shown in Figure 2. The relationship between creep strain rate and tensile stress in creep tests are shown in Figure 3. Figure 3 shows that the tensile strength of 5052 series aluminum alloy declined and creep deformation of 5052 series aluminum alloy by annealing temperature increased.

Table 1. Creep test condition

Temperature	Applied stress	Test time
°C	MPa	hour
350	11.70, 17.55, 23.40, 29.25	8.1
300	18.3, 27.5, 36.6, 45.8	8.1
250	31.5, 47.25, 63.00, 78.75	8.1

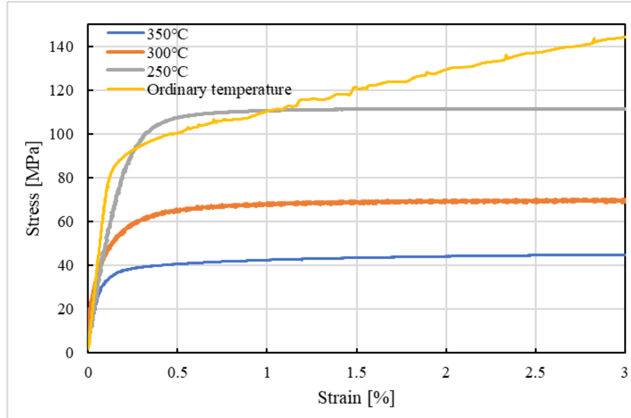
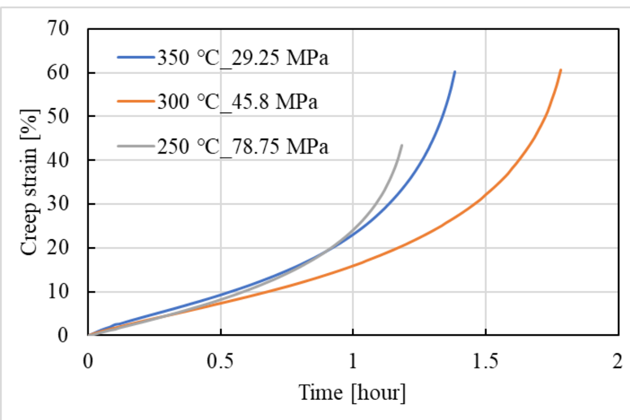
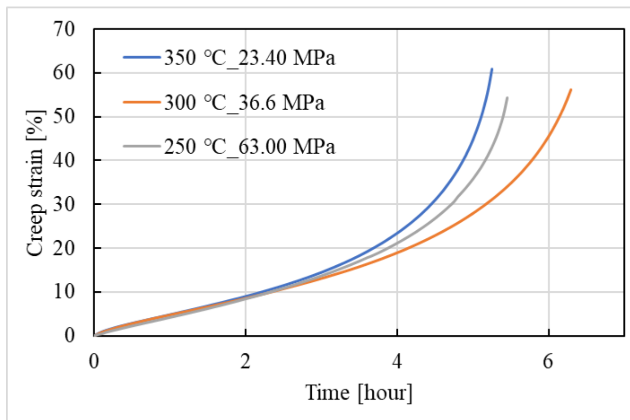


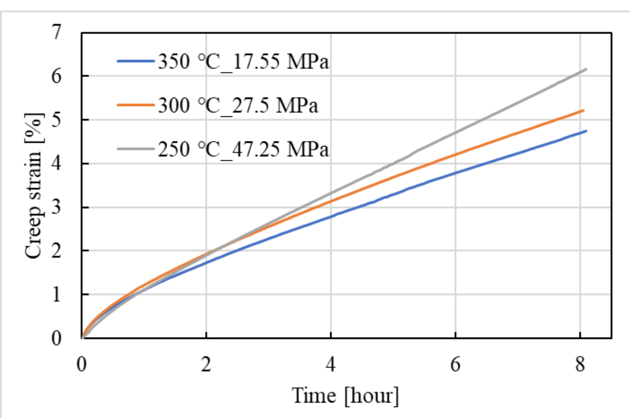
Figure 1. Stress-strain curve(tensile rate: 1mm/min)



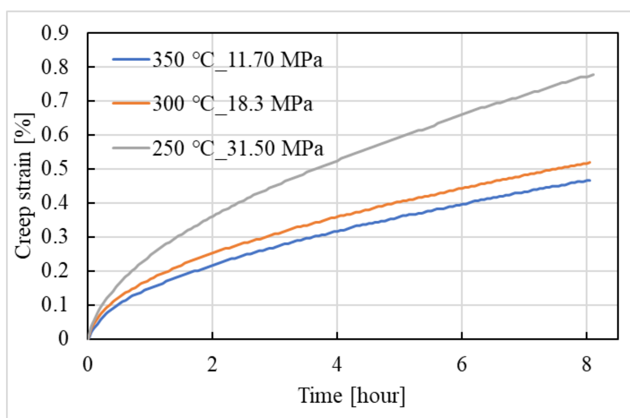
Tensile stress of 75% of 0.2% yield strength



Tensile stress of 60% of 0.2% yield strength



Tensile stress of 45% of 0.2% yield strength



Tensile stress of 30% of 0.2% yield strength

Figure 2. Creep strain-time relationships

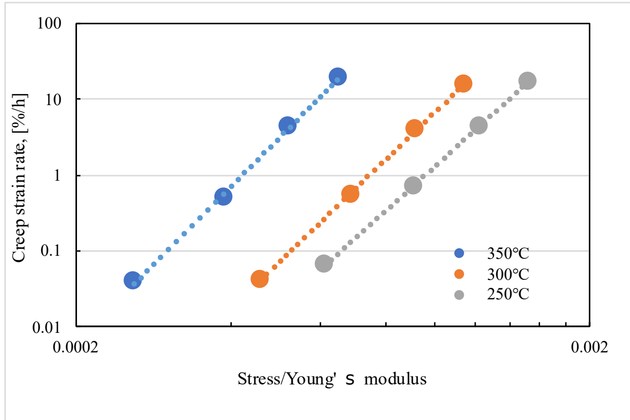


Figure 3. Creep strain rate-stress relationship

Calculation Model for Predicting Stress After Annealing

The constitutive equation given for Norton's steady-state creep law is given by Equation (1) :

$$\frac{d\varepsilon_c}{dt} = A \cdot \left(\frac{\sigma}{E}\right)^n \tag{1}$$

where ε_c represents the creep strain, t represents annealing time, A represents a positive coefficient determined by factors such as temperature, material properties, grain size, and dislocation density, σ represents stress. E represents Young's modulus, n represents stress exponent.

Regarding the stress relief model, it is known from the research by Abhishek et al. [6]. The relational expression between initial stress σ_0 before annealing and the stress $\sigma(t)$ after annealing time t is given by Equation (2) :

$$\sigma(t) = sgn(\sigma_0) \cdot \left(\frac{A \cdot (n-1)}{E^{n-1}} \cdot t + |\sigma_0|^{1-n}\right)^{\frac{1}{1-n}} \tag{2}$$

where *sgn(x)* is the function that *sgn(x)* is +1 if *x* is positive, and *sgn(x)* is -1 if *x* is negative. This Equation (2) is derived from Equation (1).

When calculating the constants *E*, *A*, and n in Equation (2) from Figures 1 and 3, the results are as shown in Table 1.

By substituting these parameters of Table 2 into Equation (2), the stress relaxation behavior was calculated. Specifically, the relationship between the stress before and after annealing when the annealing time was fixed at 3 hours was calculated and is shown in Figure 4. The relationship between the annealing time and the stress after annealing when the initial stress before annealing was fixed at 80 MPa was calculated and is shown in Figure 5.

Table 2. Young's modulus and parameter of stress relaxation characteristic prediction equations

Temperature	**Young's modulus, *E***	**A**	**n**
°C	MPa	%/hour	-
Ordinary temperature	71.9	-	-
250	51.8	2.85×10^{18}	6.114
300	40.1	2.17×10^{20}	6.504
350	45.1	1.00×10^{23}	6.817

Figure 4 shows that residual stresses above 40 MPa before annealing are almost relaxed to a constant stress level by annealing at temperatures between 250°C and 350°C. Additionally, it shows that stress after annealing declines with higher temperatures. On the other hand, for initial stresses below 10 MPa, there is minimal relaxation observed with annealing at temperatures between 250°C and 350°C because the initial stress before annealing is the source of creep deformation.

Figure 5 shows that, if an initial stress before annealing was fixed at 80 MPa, significant stress relaxation occurs with just 1 hour of annealing at temperatures between 250°C and 350°C. Figure 6 shows that linear extensions of the annealing time from

1 hour to 1.5 hours, 2 hours didn't improve stress relaxation. This shows exponential extensions of the annealing time from 1 hour to 10 hours, 100 hours are needed to promote stress relaxation.

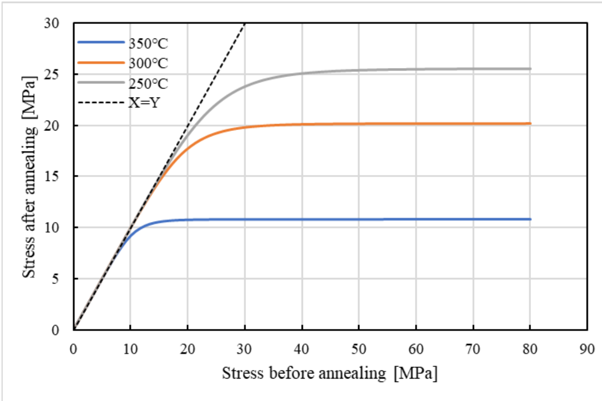


Figure 4. Stress before and after annealing (annealing time: 3 hours)

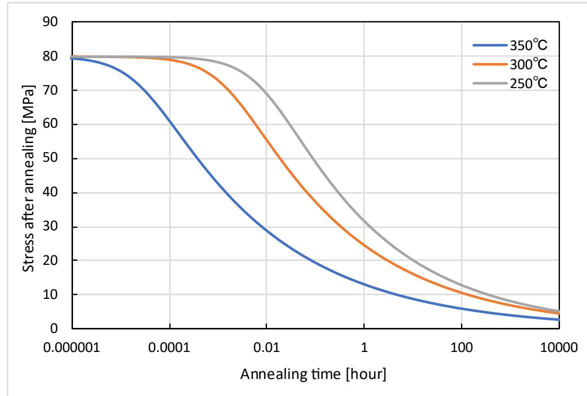


Figure 5. Relationship between stress after annealing and annealing time (stress before annealing: 80 MPa)

Calculation Model for Predicting Warpage of Plates After Annealing

We calculated the relationship between warpage before and after annealing based on the stress relaxation model in Equation (2).

Figure 6 shows a schematic diagram of the annealing process, and Figure 7 illustrates the flow of calculation model. In stress relief annealing, the warped plate is flattened by applying external forces, by stacking base plates before annealing is carried out to fix a flat state[6]. Based on the following assumptions, a simplified calculation model was developed to estimate the warpage height before and after annealing from the stress distribution before annealing:

- Stresses within the plates are only uniaxial tensile-compressive stresses in the longitudinal direction.
- Creep deformation occurs only during the soaking period. It is disregarded during temperature increase and decrease.
- The plate during annealing is perfectly flat.
- Plastic deformation is ignored, and only elastic deformation and creep deformation are considered.
- The cross-section of the plate is always flat in the thickness direction and vertical to the central axis of the plate thickness.

The relationship between stress before and after the soaking process (between (iii) and (iv) in Figure 7) is given by Equation (2). The creep deformation during the heating process (between (i) and (iii) in Figure 7) and the cooling process (between (iv) and (v) in Figure 7) are disregarded. So, the elastic strain of the plates remains constant during the heating process and the cooling process. During these periods, the relationship between stress σ and Young's modulus E is given by Equation (3):

$$\frac{\sigma}{E} = constant \tag{3}$$

The warpage height in this report is represented by the distance between a base plate and the top of the warpage when placing the plate on the base plate, as shown in Figure 8. A flow for calculating the warpage before stacking by the stress distribution

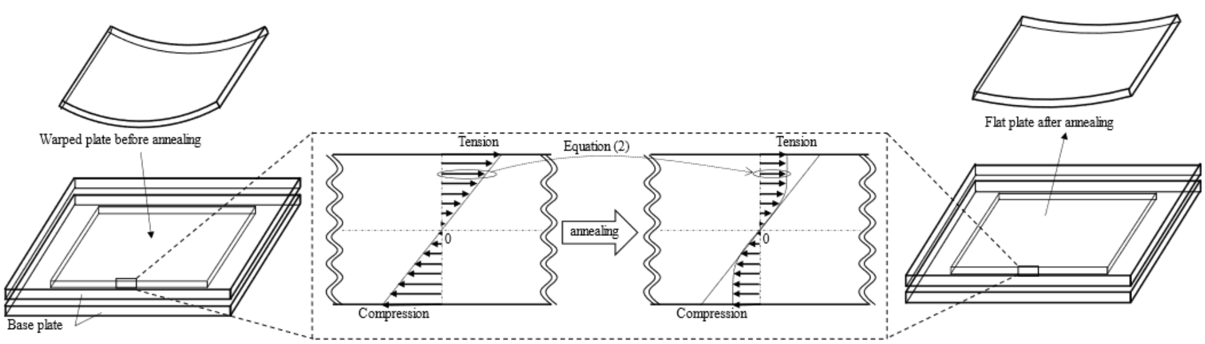


Figure 6. Schematic diagram about simple calculation model of stress relaxation during plate annealing process

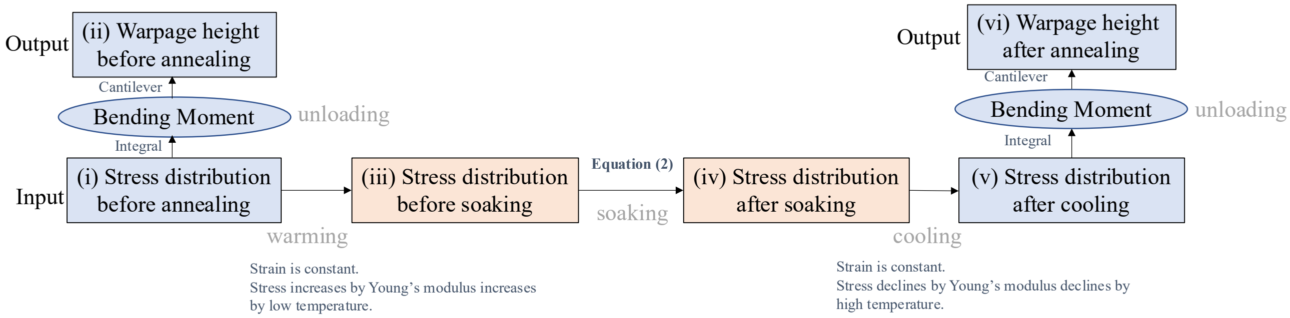


Figure 7. Calculation flow of plate annealing process

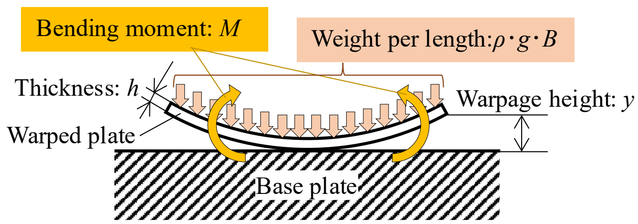


Figure 8. Definition of parameters of warpage plate on the base plate

of the stacked plate (between (i) and (ii) and between (v) and (vi) in Figure 7) are shown. First, the bending moment M is calculated from the stress distribution $\sigma(x)$ within the thickness of the plate using Equation (4):

$$M = \int_{-\frac{h}{2}}^{\frac{h}{2}} (\sigma(x) \cdot B) \cdot x \, dx \tag{4}$$

where h represents the thickness of the plate, x represents the coordinate in the thickness direction with the center of the thickness as zero, B represents the width of the plate. On the other hand, assuming a simply supported beam of length l_g, calculate the bending moment M_g due to self-weight with Equation (5):

$$M_g = \frac{\rho \cdot g \cdot B}{2} \cdot {l_g}^2 \tag{5}$$

where ρ represents the density of the plate. g represents gravitational acceleration. Assuming that the length of the plate is sufficiently long. The length l_g of the plate lifted by warpage when placed on a base plate is the length at which the bending moment M due to residual stress matches the bending moment M_g due to self-weight. This length l_g is calculated by the following Equation (6):

$$l_g = \sqrt{\frac{2 \cdot M}{\rho \cdot g \cdot B}} \tag{6}$$

The shorter of the length l_g and half of the length of the plate is the actual length l of the plate lifted by warpage when placed on a base plate. The warpage height y of the plate is the amount subtracted from the warpage height y_M due to residual stress to the warpage height y_g due to self-weight. These lengths of y_M, y_g and y are calculated with Equations (7), (8), and (9):

$$y_M = \frac{M \cdot l^2}{2 \cdot E \cdot I} \tag{7}$$

$$y_g = \frac{\rho \cdot g \cdot B \cdot l^4}{8 \cdot E \cdot I} \tag{8}$$

$$y = y_M - y_g \tag{9}$$

Parameter I represents the moment of inertia of the area of the plate, which is calculated by Equation (10):

$$I = \frac{B \cdot h^3}{12} \tag{10}$$

Using this calculation model, the behavior of C-warpage of a 5052 series aluminum alloy plate with a thickness of 12mm, length of 3050mm, and width of 1525mm during stress relief annealing at temperatures between 250℃ and 350℃ was calculated. The relationship between the warpage before and after annealing when the annealing time (soaking time) was fixed at 3 hours was calculated and shown in Figure 8. The relationship between the annealing time (soaking time) and the warpage after annealing when assuming an initial warpage of 53mm before annealing was calculated and presented in Figure 9.

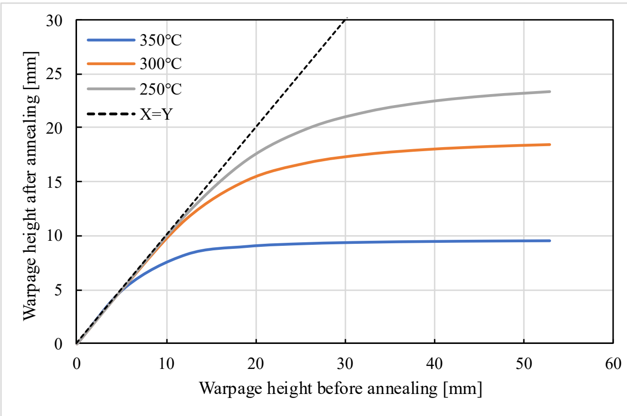


Figure 8. Warpage height before and after annealing (annealing time: 3 hours)

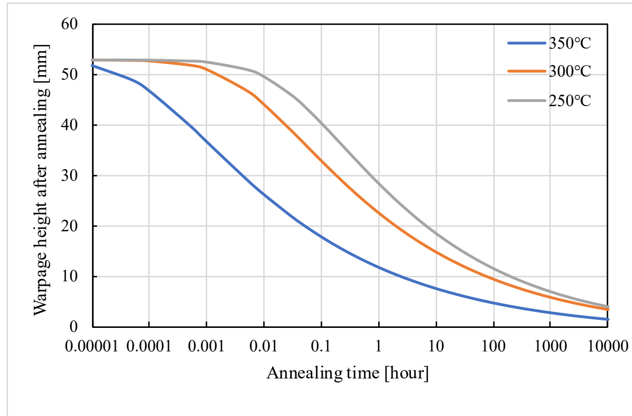


Figure 9. Relationship between warpage height after annealing and annealing time (warpage height before annealing: 53 mm)

Figure 8 shows that it is possible to reduce significant warpage of 25mm or more for a 5052 series aluminum alloy plate with a thickness of 12mm, length of 3050mm, and width of 1525mm through annealing at temperatures between 250℃ and 350℃. However, reducing small warpage of less than 5mm is considered difficult.

Figure 9 showed that for linear extensions of the annealing time from 1 hour to 1.5 hours, 2 hours didn't improve warpage correction. It showed that for exponential extensions of the annealing time from 1 hour to 10 hours, 100 hours are needed to improve warpage correction.

CONCLUSIONS

The development of a predictive calculation model for warpage correction of plates by stress relief annealing was attempted, and the following conclusions were obtained due to the calculation results:

- It is possible to calculate the warpage correction of the plate material through annealing based on the behavior of creep deformation.
- Warpage correction of the plate material through annealing exhibits similar behavior to stress relaxation through creep deformation.
- Warpage correction of the plate material through annealing is effective when the initial warpage before annealing is significant, but it is mostly ineffective when the initial warpage is small.
- To enhance the corrective effect of warpage correction through annealing by extending the annealing time, it is necessary to exponentially increase the annealing time to achieve noticeable effects.

In conclusion, while it is possible to create plate materials with warpage below a certain threshold through stress relief annealing, achieving completely flat plates is challenging. It was found that increasing the temperature slightly is more effective than extending the annealing time to reduce warpage as much as possible.

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