Depth Profile of Residual Stresses to Analyze Textures in Extruded A6XXX

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Abstract. The extruded profiles of A6XXX alloys have a textured surface structure, different from those having the inner cube and Goss orientations. This structure possibly contributes to the decrease in bending strength. Although the mechanism of degradation has been discussed for precipitates, it is necessary to reconsider it from the viewpoint of residual stress distribution. In this study, we first determine the optimal method to evaluate the residual stress in a textured structure. The cosα method with 3-axis oscillation successfully yielded highly precise residual stress values even in extruded aluminum alloys. Although the inner layers of A6063 and A6005C had the cube and Goss orientation, the surface layer at a depth of ~400 μm had a (112) orientation in A6063 and that at ~200 μm had a (110) orientation in A6005C. The residual stress increased further from the surface, and changes in the preferred orientation corresponded well with those of residual stress, especially in A6005C. It is suggested that the residual stress increases as the tensile strength increases.

1. Introduction
The A6XXX alloys, undergo aging and precipitation to form Mg₃Si precipitates. Because of their lower deformation resistance, the extruded profiles of A6XXX alloys have been used mainly in the field of architectural products and transportation equipment. Their mechanical properties are influenced by the recrystallized structure having a preferential orientation.

The decreased bending strength of the extruded A6XXX alloys may be due to their textured structure, which consists of both surface and inner cube and Goss orientations in the extruded direction. This is caused by the shear friction of the flowing aluminum in the die bearing area. It is important to determine the formation mechanism of the texture due to shear stress as well as understand how the profile texture is controlled by controlling the applied stress and improving the mechanical properties of the profile.

Previous studies have attempted to explain the texture formation mechanism in extruded profiles of alloys or metals from the viewpoints of precipitation density, size, and existence area in the grain boundaries or matrix. However, the extruded profile properties have not been discussed in terms of the stress field applied from the die and aluminum flow. In this study, we have conducted high-precision residual stress measurements of the aluminum extrusion profiles with preferred orientation and large crystal grains using the cosα method.

The residual stress is usually measured from the diffracted X-ray peak shift with incident angle ψ, which is well known as the sin²ψ method. The residual stress values can be quantitatively calculated using the following equation:

\[
\sigma = \frac{\Delta d}{d} \cdot \frac{E}{1 - \nu^2}
\]

where \(\Delta d\) is the X-ray peak shift, \(d\) is the lattice parameter, \(E\) is the Young's modulus, and \(\nu\) is the Poisson's ratio.


\[
\sigma_x = -\frac{E}{2(1 + \nu)} \cot\theta_0 \frac{\pi \partial 2\theta}{180 sin^2\psi}
\]

(1)

where, \(\sigma_x\) : residual stress  
\(E\) : Young’s modules  
\(\nu\) : Poisson's ratio  
\(\theta_0\) : standard Bragg angle  
\(\eta\) : complementary angle, \(\theta\)  
\(\psi\) : X-ray incident angle

Through the \(\sin^2\psi\) method, the diffracted peak shift with \(\psi\) can be measured; however, it is difficult to apply textured material with large crystal-grain-like extruded aluminum profiles to this research because they recrystallized easily through a highly thermodynamic process. Therefore, X-ray diffraction analysis subjected to the \(\sin^2\psi\) method shows a discontinuous Debye-Scherrer ring (D-S ring), preventing accurate calculation of the peak shift. We applied the \(\cos\alpha\) method constructed with 3-axis oscillation and quickly obtained a full diffraction ring.

The \(\cos\alpha\) method, first proposed by Taira and Tanaka\(^4\), utilizes the entire D-S ring recorded on a two-dimensional detector taken by single exposure to X-rays. Normal and shear stresses are obtained simultaneously. The residual stress values were quantitatively calculated using the following equation:

\[
\sigma_x = -\frac{E}{1 + \nu} \frac{1}{sin^2\eta sin^2\psi_0} \frac{\partial \varepsilon_{a1}}{\partial \cos\alpha}
\]

(2)

where, \(\alpha\) : D-S ring angle  
\(\sigma_x\) : residual stress  
\(E\) : Young’s modules  
\(\nu\) : Poisson's ratio  
\(\eta\) : complementary angle, \(\theta\)  
\(\psi_0\) : X-ray incident angle  
\(\varepsilon_{a1}\) : strain

Although Taira’s method takes a long time to detect the D-S ring using X-ray films, the use of an imaging plate detector solved this problem, making this method applicable for stress analysis. The simple optical system of the \(\cos\alpha\) method made the stress analyzer portable, smaller, lighter, and more convenient to use for on-site and field measurements. By using a new \(\cos\alpha\)-based analyzer, the time required for a single stress measurement is shortened to the order of minutes. We investigated the correlation between the residual stress distribution and cross-sectional grain orientation and explored the possibility of structural control by a stress field to improve mechanical properties.

2. Experimental

2.1. Specimen preparation

In this study, typical ISO, JIS-A6063, and A6005C alloys, whose chemical compositions are listed in Table 1, were used as the specimen. A6063 is the most commonly used alloy for extrusion, with a tensile strength of approximately 200 MPa. The tensile strength of the A6005C, which falls in the middle range of the A6XXX alloy series, is approximately 280 MPa. The A6005C has a higher content of Mg, Si, and Cu components and poorer extrudability than those of A6063. The effect of strength on the residual stress was investigated by comparing these two alloys having different tensile strengths.
The thermal cycle for extrusion and the cross-section of the extruded profile are shown in Fig. 1. Casted aluminum billets were homogenized at 570 °C for 3.7 h and extruded using a 2300 Metric-ton direct extrusion press machine. The extruded profiles were immediately cooled from 570 °C to room temperature by a water spray at 3000 °C/min, followed by artificial aging treatment at 200 °C for 2.5 h as T6 treatment. The cross-section of the extruded profiles had a square hollow shape.

2.2. Experimental procedure
Specimens were cut as ~ 20 × 20 mm square plates from the extruded profile. To measure the residual stress distribution in the depth direction from the surface, the specimens were electropolished 30–400 μm from the surface, which was masked on the opposite side to precisely identify the polishing amount. The electrolyte used was a solution of 6 vol% perchlorate acid ethanol at 0 °C and an applied voltage of 15 V. The polishing amount was measured by a micrometer and was approximately 50 μm after 20 min of polishing.

The X-ray measurement conditions of the sin²ψ and cosα methods are listed in Table 2. The SmartLab system (Rigaku Corp.) was used for the X-ray sin²ψ method. We used (422) diffraction with Cu-Kα radiation at 2θ = 137.46 deg and an oscillation angle of 5 deg in the φ axis; we obtained stresses using Young's modulus (E) = 69.3 GPa and Poisson’s ratio (ν) = 0.35. The X-ray diffraction in the cosα method was measured using a portable μ-X360s analyzer manufactured by PULSTEC Industrial Co., Ltd. We used (311) diffraction under Cr-Kα radiation at 2θ = 138.48 deg and obtained stresses using the same E and ν values. The μ-X360s analyzer used robotic 3-axis oscillation (ψ), in-plane rotation axis (φ), and was perpendicular to the incident X-ray axis (ω) by 10 deg (±10 deg) for each, obtaining a continuous D-S ring in 60 s. The X-ray sin²ψ method of the 1-axis swing achieved no accurate peak shift and an unreliable residual stress value because of the large grain size and preferred orientation of the aluminum profiles.

Table 1 Chemical composition of A6063 and A6005C

| Alloy   | Component (mass%) | Mg | Si | Cu | Fe | Mn | Cr | Al |
|---------|-------------------|----|----|----|----|----|----|----|
| A6063   |                   | 0.55 | 0.40 | 0.10 | 0.16 | 0.00 | 0.00 | Bal. |
| A6005C  |                   | 0.60 | 0.60 | 0.20 | 0.15 | 0.02 | 0.04 | Bal. |

Table 2 Measurement conditions for extruded profiles by the X-ray sin²ψ and cosα methods

| Method                | sin²ψ     | iso-inclination | cosα          |
|-----------------------|-----------|-----------------|---------------|
| Apparatus             | Rigaku Corp. SmartLab | Pulstec Ind. μ-X360s |
| X-ray type            | Cu-Kα, λ = 1.54059 Å | Cr-Kα, λ = 2.28970 Å |
| X-ray power           | 45 kV, 200 mA | 30 kV, 1.5 mA |
| Collimator size       | 10 mm × 1 mm | φ = 1.0 mm |
| Diffraction           | Al(422) 20 = 137.46 deg | Al(311) 20 = 139.32 deg |
| X-ray incident angle  | 0 ~ 40.2 deg | 30 deg |
| Oscillation angle     | φ = 5 deg | ψ, φ, ω = 10 deg (±10 deg) |
| Irradiation area      | 11.0 mm² | φ = 2.0 mm |
3. Results and discussion

3.1. Residual stress obtained by the two measurement methods

Figure 2 shows the Al (422) diffraction peak shift measured by the X-ray sin²ψ method and the 2θ - sin²ψ diagram with φ angle oscillation in A6063 at the surface. Irregular variation in the peak position and intensity prevented the observation of an accurate peak shift. The sin²ψ diagram was not straight, and the calculated σₓ was 50±147 MPa, which had an unreliable high standard deviation.

Figure 3 shows a typical D-S ring obtained by the X-ray cosα method with ψ, φ, and ω oscillation for Al (311) of the extruded A6063 profile at the surface. Although the specimen has a large crystal grain and textured surface, a continuous ring was successfully obtained. The calculated σₓ was −27±5 MPa, which had a reliable standard deviation. Thus, residual stress distribution was measured by the cosα method hereafter.

Fig. 2 (a) Al (422) diffraction peak shift measured in A6063 by the X-ray sin²ψ method and (b) 2θ - sin²ψ diagram with only φ axis oscillation. Accurate peak shift could not be identified because of irregular variation in peak position and intensity. The sin²ψ diagram was not straight. The calculated σₓ was 50±147 MPa.

Fig. 3 (a) D-S ring obtained by the X-ray cosα method with ψ, φ, and ω oscillation for Al (311) of the extruded A6063 profile and (b) the cosα diagram. Although the specimen has a large crystal grain and textured surface, a continuous ring was successfully obtained. The calculated σₓ was −27±5 MPa.
3.2. Residual stress distribution of extruded A6063 profile

Figure 4 (a) shows a cross-sectional inverse pole figure (IPF) map of the A6063 profile, in which strong cube and Goss orientations of the inner layer can be seen. The surface layer at a depth of ~400 μm exhibited the (112) orientation\(^5,\,^6\). Fig. 4 (b) shows the residual stress distribution from the surface to a depth of 150 μm.

The principal stress, \(\sigma_1\), ranged from 4 to –4 MPa from the surface to 40 μm and gradually increased to 11 MPa at a depth of 150 μm. The shear stress, \(\tau_{xy}\), was –3 MPa at the surface and increased gradually to 27 MPa at a depth of 150 μm. The von Mises stress, \(\sigma_{VM}\), was 10 MPa at the surface and increased to 66 MPa as the depth increased.

![Fig. 4 (a) Cross-sectional view of IPF map (ED) of A6063 profile. (b) Depth profile of stresses: principal stress \(\sigma_1\), shear stress \(\tau_{xy}\), and von Mises stress \(\sigma_{VM}\).](image)

3.3. Residual stress distribution of extruded A6005C profile

Figure 5 (a) shows the same correspondence of A6005C. The inner layer structure had cube and Goss orientations, in which (100) faced to the extrusion direction and the surface layer had the (110) orientation.

The depth profiles of the residual stresses in A6005C are shown in Fig. 5 (b). The principal stress, \(\sigma_1\), was compressive from the surface to a depth of 75 μm and increased at a depth of ~105 μm, showing a maximum of 27 MPa, followed by a compressive change at a depth of 220 μm, finally increasing to 300 μm and plateuing near zero to 400 μm. The shear stress, \(\tau_{xy}\), exhibited the opposite tendency. The von Mises stress, \(\sigma_{VM}\), which was the lowest at the surface, increased to 105 μm and showed a maximum of 118 MPa, similar to \(\sigma_1\).

The boundary between the inner and surface layers was clear with a grain growth region just below the boundary. The first maximum value of \(\sigma_{VM}\) at 105 μm corresponded well to the (110) region, and the range between the first maximum at 105 μm and the second local maximum at 300 μm corresponded to the grain growth region.
4. Conclusion

The study proposed the method to precisely measure stresses in an extruded profile of A6XXX alloy with coarse grains and preferred orientation. In addition, we clarified the relationship between the stress distribution in the cross section and the IPF map of the texture.

The results are summarized as follows:

(1) The cosα method with 3-axis oscillation allowed for the high-precision measurement of the aluminum extrusion profile with a preferred orientation and large crystal grain. The sin^2ψ method could not obtain an accurate peak shift or reliable σ_x value.

(2) The inner layer structures of A6063 and A6005C had cube and Goss orientations, with a dominant cube orientation. The surface layer at a depth of ~400 μm had a (112) orientation in A6063 and that at a depth of ~200 μm had a (110) orientation in A6005C. The residual stress increased further from the surface. However, the absolute value of σ_M of A6063 was lower than that of A6005C. It is suggested that the residual stress increases as the tensile strength increases.

(3) The changes in the preferred orientation corresponded well with those of residual stress. The boundary of the surface preferred orientation (110) and inner (100) matched well with the first local maximum of σ_M, whereas the grain growth area of A6005C ranged from the first to the second local maximum of σ_M.

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