Residual Stress Behavior of Rolled Aluminum Alloy A2024T3 in a Thin Plate During Cyclic-Tension Fatigue Studied Using Ultrasonic Horizontally Polarized Shear Waves

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The cyclic-tension fatigue in a rolled thin-plate of aluminum alloy Al–4Cu–1Mg was evaluated nondestructively using a horizontally polarized shear wave (SH) transmission method under optimized measuring and analyzing conditions. The propagation time of the SH waves, which contained elements of reflected waves, had three distinct stages, the first, middle and final ones, during the fatigue process. The variation of the propagation time was dominated by the residual-stress field during the fatigue progress, as an acoustoelastic effect. The change in the stage of the variation can be elucidated by balance points for the redistribution of the residual stress, which clearly told us the degree of progression of the fatigue in the thin plate. [doi:10.2320/matertrans.M2009356]

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1. Introduction

In general, the variation of the residual stress (i.e., the behavior of the lattice strain) during fatigue progression is one measure of predicting fatigue life. X-ray diffraction (XRD)1–3 and neutron diffraction (ND)4) have been also used to evaluate the stress or its full-width at half-maximum (FWHM) value. However, these methods are difficult to apply in the field. Moreover, these methods usually require cutting out a sample. Even if the test can be performed nondestructively on site, the area evaluated is often restricted because of the measurement principles and the actual structural limitations.

By contrast, ultrasonic methods can be adapted for field use more easily than diffraction methods and can be used to evaluate the residual stress field. Since ultrasonic waves are propagating elastic waves with high frequencies, the propagation behavior is actually affected by the lattice strain. This is called acoustoelasticity, which is a phenomenon that follows the change in the elastic modulus caused by a change in the atomic distance.5) Although much attention has been devoted to the nonlinear behavior of fatigue that arises from the dislocation motion,6–9) few studies have focused on the behavior of the residual stress as acoustoelasticity.10,11) The emphasis point for evaluation of fatigue is the difficulty in accurately repeating measurements of slight stress variations.

In a previous paper,11) using a nonhygroscopic couplant,15) we verified that surface horizontally polarized shear (SH) waves could detect the variation in the residual stress of aluminum alloy A2024T3 in a thick plate during cyclic-tension fatigue by help of the vertically polarized shear wave (SV) reflection and XRD methods. For practical use, however, since surface SH waves diffract in the material, the specimens require certain thickness without the influence of reflected waves. Furthermore, the residual stress in thin plate would not behave in the same manner as in thick one due to thickness-dependent stress state.

Therefore, this present study reports trial results of the SH method for a thin plate of the aluminum alloy A2024T3 in order to develop a nondestructive ultrasonic quantitative method. We thus focus on the quantitative optimum measuring conditions and the propagation behaviors associated with the residual-stress field in this study.

2. Experimental

2.1 Materials and fatigue test conditions

The material tested in this study was A2024 (Al–4Cu–1Mg in mass%, temper T351, supplied by Frukawa-Sky Aluminum, Tokyo, Japan). The mechanical properties of the material are shown in Table 1. The specimen, which was rolled perpendicular to the longitudinal direction (LD), is shown in Fig. 1(a). The as-received specimen was subjected to a cyclic tensile stress under controlled conditions. The stress amplitude \( \sigma_a \) was 153 MPa and the stress ratio \( R \) was 0. The frequency was 30 Hz, which was controlled using a hydraulic servo fatigue tester (FT-5: Saginomiya, Tokyo, Japan). The tests were performed at room temperature.

2.2 Ultrasonic measurement and analysis

The tests were interrupted at arbitrary intervals while the specimen was removed from the fatigue machine grip. The ultrasonic SH wave measurements were performed to characterize the diffraction from the surface of the specimen. The apparatus and a block diagram of the measurement process are presented schematically in Fig. 1(b). The SH probe consisted of two facing transducers with a center frequency of 5 MHz; these were separated by a distance of 10 mm and arranged as a transmitter and a receiver, each with

<table>
<thead>
<tr>
<th>Tem</th>
<th>0.2% Proof stress [MPa]</th>
<th>Tensile strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
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<tbody>
<tr>
<td>T351</td>
<td>326</td>
<td>494</td>
<td>20</td>
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a contact area of 6 × 6 mm. The ultrasonic wave pattern was analyzed using a diagnosis and analysis apparatus (TP-1001: Toshiba Tungaloy) at a controlled temperature of 296 ± 1 K. The type of pulse was square negative (Fig. 1(c)). The input voltage, sampling frequency and averaging number were 100 V, 100 MHz, and 16, respectively. The rise time of the input voltage from 10% to 90% was 75 ns. The measuring accuracy of the system is within 1 ns in the propagation time. In this material, the acoustic anisotropy13) calculated from the propagation differences in the LD and transverse direction (TD) was quite small: approximately 0.00013. The wave propagation was aligned parallel to the LD.

2.2.1 Contact pressure and holding time
The SH probe contacted the specimen via water-free naphthenic hydrocarbon oil (Tungsonic oil H12) at room temperature. The contact pressure and holding time for the test were determined to be 2.3 MPa and 120 s, respectively, from an amplitude-stabilization test as shown in Fig. 2. The amplitude was normalized by the maximum value at a contact pressure of 2.3 MPa.

2.2.2 Incident and receiving angles of the SH probe
To analyze effective locus of the SH propagation waves passing the specimen, we first examine it using specimens with 16 kinds of slit depths. Figure 3(a) shows the maximum amplitude, A1, data of the receiving waveform at various incident and receiving angles of the SH probe as a function of the slit depth of a specimen with sufficient thickness. Subsequently, the angle of the SH probe was fixed at 21°, which gave the maximum receiving amplitude, i.e., the most effective propagation for the material. From the data, we realized that most of the energy of the wave diffracted near the surface of which the effective depth was approximately 3 mm.

2.2.3 Verification of the reflecting waves
Since the specimen used in the fatigue test is 3 mm thick, we must examine a harmful influence of reflected waves from the bottom of the specimen because ultrasonic waves radiate to every direction. Figure 3(b) shows the change in the receiving waveform for various thicknesses of the material using the SH probe. The arrows indicate the points of arrival of the reflected waves. Under the test conditions, we realized that the second peak of the receiving wave was strongly influenced by the reflected waves, and that the first peak which had the maximum amplitude also contained some elements of the reflected waves. Taking the characteristics of the complex waveform into consideration, the position of the first peak was selected as the propagation time, T1, for analysis (Fig. 3(b)).

2.3 Phase identification
To compare the results of the ultrasonic measurements with microstructures in the material during the fatigue process, we examined the structural variation using the
following methods. The fractured surface was observed using scanning electron microscopy (SEM). The surface roughness $R_a$ which was calculated as the average in the LD and TD was measured with a digital surface roughness tester (F-T-120: Taylor Hobson, Leicester, UK) at the center of the specimen before and after the test. Using the other same-lot specimen subjected to the same load conditions, the variation in the residual stress of the specimen was measured using computer-automated XRD (MAC-MXP3A: Mac Science, Yokohama, Japan) as the fatigue progressed. The residual stress was measured at the center of the specimen in the LD using Cu–K$_{\alpha}$ radiation for the Al (311) plane with an incident slit width of 0.84 mm and a slit height of 5 mm.

3. Results

3.1 Ultrasonic analysis

The specimen used in the fatigue test was destroyed after $2.7 \times 10^5$ cycles. The variations in the receiving waveforms and propagation time $T_1$ for the SH waves in the LD are shown in Fig. 4(a) and Fig. 4(b), respectively, as functions of $N/N_f$, where $N$ is the number of cycles and $N_f$ is the number of cycles to failure. Although there is little change in the receiving waveform, the data can be classified into three explicit stages, A through C. In the first stage of fatigue, in which the $N/N_f$ ratio ranged from 0 to 0.4, the propagation time decreases. In the middle stage, with a ratio of 0.4 to 0.8, it restores gradually. In the late stage, for ratios over about 0.8, it decreases again toward failure.

3.2 Material evaluations

The crack was positioned approximately 5 mm from the TD center and was within the sensing area (Fig. 5(a)). Figure 5(b) shows SEM images of the fractured surface. The crack initiation site was located laterally. The fractured surface showed definitive evidence of fatigue failure. The origin (marked “O” in Fig. 5(b)) indicates that the fracture mode is due to slip deformation. During the test we could not detect a visible crack in mm until the failure. The striation area of the fractured surface shows the crack propagated until 1.3 mm in the stage II crack growth. The tolerance for crack propagation was small enough for the sensing area. Since the specimen was unnotched, the fatigue life was thought to be almost gone for the stage I crack growth and the resulting microscopic progress in the stage II crack growth. Thus, we confirmed that the evaluation test terminated as normal: the macroscopic crack did not affect the evaluation area directly.

The receiving waveform is affected by surface roughness due to changing in the state of the grease pool. However, the variation in the surface roughness $R_a$ during the fatigue process is negligibly small for the SH wave propagation: the influence is thought to be less than 0.001 $\mu$s for the propagation time, as shown in Fig. 6. The standard curve was
determined using another A2024T3 sample with sufficient thickness.

The variation of the residual stress is shown in Fig. 7. Although the temper of the material is T351 (post-tensioned following natural aging), the initial residual stress accumulates on the compressive side to some extent. The variation in the data has also revealed three stages, A, B and C, in which the fatigue ratios dovetailed with the ratio of the SH data. In region A, the residual stress shifts to the tensile side. In region B, it decreases despite the direction of loading. Finally, in region C, it shifts back to the tensile side as fatigue failure approaches. From the synchronization in Fig. 4(b) and Fig. 7, we notice that the variation of the propagation time of the SH wave is strongly influenced by the residual stress fields.

**4. Discussion**

We consider the influencing factors of the propagation time. In fatigue process, ultrasonic velocity requires consideration of the effect by the dislocation structure. The dislocation string works as a viscoelastic machinery to the ultrasonic vibrations, and consumes the elastic energy resulting the decrease of the velocity.\(^9\),\(^14\) The reports\(^7\),\(^15\) show that the viscoelastic effects such as the harmonic and the internal friction increase exponentially in the fatigue progress of the aluminum alloys. Actually, our previous test\(^11\) using the aluminum alloy A2024T3 under the cyclic-tension fatigue shows the similar behavior: the internal friction begins to increase notably in the middle stage of the fatigue. However, the test also represents that the propagation time of the SH waves decreases with the fatigue progression. This leads that the viscoelastic effect by the dislocation motion during the fatigue is lightly affected on the measuring result. In fact, the velocity change of the SV waves obtained collaterally with the SH test reveals poor correlation to the viscoelasticity. Moreover, in the first place, the unidirectional increment of the viscoelasticity does not match with the characteristic behavior of the propagation time (Fig. 4(b)).

On the other hand, we must consider the effect by the residual stress. Stress field changes the elastic moduli and the density of the medium, resulting in velocity change as an acoustoelasticity. However, the velocity change by the acoustoelasticity has been reported as a very small degree.\(^16\) Assuming the variation of the propagation time in Fig. 4(b) is caused by the velocity change due to the residual stress shift in Fig. 7, the acoustoelastic constant is calculated as approximately 0.0062%/MPa. This value is considerably large compared to the ones which were obtained by the reflection techniques in other kinds of the aluminum alloy: approximately 0.0016\(^\pm\)0.0035\(^\%\)/MPa. Therefore, the velocity change due to the acoustoelasticity would not be the dominating factor for the variation. Here, as evidenced by Fig. 3(a), the SH waves used in this study are diffraacting in the medium to the depth of mm: the waves are not pure and simple surface-wave. The diffraction of the waves is based on the Huygens-Fresnel’s principle.\(^19\),\(^20\) Thus, the refracting phenomenon\(^21\) by the residual stress field, i.e., the propagat-
different from the reflecting method. This point is
shift, should be considered for an analysis of the propagation time. In other words, in the
diffraction method, the variation of the propagation time does
describe the velocity change directly. This point is different from the reflecting method.

In the previous papers, we have advanced the theory that the diffraction angle of the SH waves shifts under stress loading. The schematic energy-flux model and the effect of the acoustoelasticity, which brings energy-path shift, are represented in Fig. 8(a) and (b)–(c), respectively. The mechanism is attributed to the change in the vector component of the acoustic energy caused by anisotropic changes of the shear stress tensor due to the applied stress. When we assume the two-dimensional x-y plate to which a stress is applied in the x and y directions of a Cartesian coordinate system, the acoustic energy flow $P$ of the SH wave propagating in the x-y plane at an arbitrary angle $\alpha$ from the specimen surface can be expressed by the following forms:

$$ P = \sqrt{P_x^2 + P_y^2} = \sqrt{\left(\frac{1}{2} \mu \tau_{xz}\right)^2 + \left(\frac{1}{2} \mu \tau_{yz}\right)^2} $$

where $P_x$ and $P_y$ are the energy flux of direction $x$ and direction $y$, respectively, $\mu$ is the displacement of the SH wave to direction $z$, $\tau_{xz}$ and $\tau_{yz}$ are the shearing stress of direction $z$ at $x$ plane and $y$ plane, respectively, and $\mu$, $A$, $\xi$ and $\beta$ are the shear modulus, the displacement amplitude, the number of waves and the element of wave number to direction $z$, respectively. Thus, the energy flow $P$ would be bended based on the stress condition of the medium, i.e., the variation of the correlation between the interatomic spacings of the direction $x$ and $y$ could tell us whether the diffraction angle $\alpha$ increases or decreases. When a tensile stress is applied, the propagation region of the wave energy along the stress becomes shallower, while it becomes deeper for a compressive stress (Fig. 8(b)). As a result, the receiving waveform obtained by the facing SH probe affects the propagation time, amplitude and damping (Fig. 8(c)). Therefore, we can interpret the variation in the propagation time shown in Fig. 4(b) by the acoustoelastic theory. The residual stress shifts to the tensile side in region A, to the compressive side in region B, and finally back to the tensile side in region C as fatigue failure approached, as can be seen from the variation in the residual stress in the LD obtained from the XRD analysis (Fig. 7).

Here, we consider the reason why the ‘V’ type variation in propagation time occurred (Fig. 4(b)) in terms of stress-induced reflection of waves. The previous study of 6-mm-thick aluminum alloy A2024T3 performed using SH and XRD methods revealed that the variation of the residual stress field which accumulates on the compressive side initially shifts to the tensile side gradually with cyclic tension. From the variation of Fig. 7, the stress field shifts to the tensile side gradually, the point of reflection would be shifted according as the characteristic variation in the propagation time. The propagation path of the reflected wave at a reflecting angle $\theta$ is given by

$$ L = t \cos \theta + \sqrt{t^2 + (d - t \cdot \tan \theta)^2} $$

where $t$ and $d$ are the thickness of the specimen and the span between the transducers, respectively. Figure 9 shows the amount of reflecting-angle shift equivalent to the path length change, provided that the variation in the propagation time $T_1$ is caused by a shift in the reflecting wave: the reflection point shifts to the receiver side. Assuming that the acoustic velocity is a constant 3,116 m/s throughout the fatigue progress, the variation in the propagation time at regions A and B corresponds to approximately 47 $\mu$m. This requires variation in the reflecting angle of approximately 9°, which is too large. From Snell’s law, the amount of variation in the incident angle is equivalent to approximately 1.2°, i.e., an incident angle of 22.8°. The variation amount in the receiving waveform throughout the fatigue process is, indeed, very small (Fig. 4(a)). Figure 3(a) do not support the dynamic angle change due to diversion of SH waves: the angle exceeds the critical angle. The shift in the point of reflection, furthermore, cannot explain the decrement in region C. Judging from these results, although the propagation time $T_1$ is thought to contain elements of the reflecting waves, the characteristic variation in the three regions is dominated not by the shift in the point of reflection, but the path change.

![Fig. 8](image-url)
of the diffracting waves due to the acoustoelasticity: the change in the propagation time \( T_1 \) corresponds to the change in the residual stress, as shown by the XRD data (Fig. 7).

Then, we must consider why the accumulation side switches with the degree of fatigue despite of the unidirectional cyclic tension. For this reason, K. Mitsunaga and M. Ishibashi\(^{23}\) have reported that there are similar three stages, A through C for variation of the residual stress in an iron-based material. In the report, the shift mechanism is thought to be by the power balance between local yielding, resulting changes in intrusion and extrusion, and the growth of micro cracks. In the stage A, the residual stress is rapidly relieved (averaged as a whole) by local yielding as if the effects of thermal action. By contrast, in the stage B, the stress accumulation on the compressive side is dominant for the development of intrusion and extrusion. The development of intrusion and extrusion is tensile plastic deformation at the surface apparently, and would produce a compressive residual-stress field. In the stage C, local yielding and the stress relief resulting from micro-cracks come to dominate than the stress accumulation factor. This mechanism is supported by the finding that the material, which does not have an initial compressive stress, has only two stages: B and C.\(^{23}\) Therefore we think that the similar mechanism of redistribution for the residual stress dominates for the aluminum alloy we studied.

Lastly, we consider the reason why the variation in the residual stress showed a different trend for the 6-mm-thick A2024T3 of which the stress shifts to the tensile side monotonically with cyclic tension.\(^{11}\) This suggests that the residual-stress behavior with the fatigue progress depends on the specimen thickness. In the thick plate, the residual stress could accumulate to the tensile side monotonically due to the strong restraint in the thickness direction, i.e., under a state of plane strain. In other words, in the thin plate of interest, the influence by the development of inclusion and extrusion could become evident as stage B due to the weak restraint in the thickness direction. Under the state of a plane stress the strain by the loading is free in dimension. Thus the strain in the LD of the local yielding could be relatively smaller than the one in the state of plane strain. This interpretation requires further study of the effects of different specimen thicknesses and initial states of the residual stress. Furthermore, the state of the surface roughness, which could dismiss the strain by the development of intrusion and extrusion, is also to be considered.

To detect the variation in the residual stress accurately, as mentioned previously, we must consider the influence of dislocation which affects the acoustic velocity. Although the damping ratio of the amplitude is relatively favorable for the residual stress interaction,\(^{11}\) it is difficult to use the ratio because of the harmful influence by the reflecting waves in a thin plate. The influence of dislocation motion needs further investigation.

In this study, we demonstrated that the variation in the residual stress field can be grasped vividly using the SH method compared with the XRD method. This provides the simple, rapid, nondestructive tool for evaluation of residual stress in the field. We should pay attention to the stress transition from stage B to stage C for fatigue-life prediction in this material.

5. Conclusions

The acoustic characteristics of the thin plate of aluminum alloy Al–4Cu–1Mg under cyclic-tension fatigue were evaluated in a nondestructive manner using a SH wave diffraction method. In the method, the propagation time had three distinct stages, the first, middle and final ones. In the first stage, up to a fatigue ratio of about 0.4, the propagation time decreased, while in the middle stage, from a ratio of 0.4 to 0.8, the time increased. In the final stage, at a ratio over 0.8, it decreased again to fatigue failure. This curious variation was dominated by the change in the residual-stress field based on acoustoelasticity and the trend change is thought to be caused by the balance shift of the stress redistribution. The variation in the surface roughness and the resulting reflecting waves was negligible in terms of the change in the propagation time.
Comparison with the results of the thick plate of aluminum alloy which the residual-stress field showed monotonic variation to the loading side, it is thought that the stress-variation for the thin plate suggests a state of plane stress. Thus the SH method can be used as a useful probe for the degree evaluation of fatigue progression of the alloy.

REFERENCES