High Accurate Residual Stress Evaluation by Deep Hole Drilling Technique Considering Three-dimensional Stress Fields *

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The deep hole drilling (DHD) technique has received much attention in recent years as a method for measuring through-thickness residual stresses. However, some accuracy problems occur with the DHD technique. One reason is that the traditional evaluation formula assumes that the stress condition around the reference hole is two-dimensional plane stress. In this study, a new evaluation formula and procedure are proposed using three-dimensional stress functions to evaluate the residual stress more accurately. Then, a known stress field is evaluated by the traditional formula and the new formula using the finite element method to compare the accuracy of the both results. These results indicate that the proposed formula can evaluate the residual stress better than the traditional formula can.

Key Words: Deep hole drilling technique, Residual stress, Three dimensional stress condition

1. Introduction

Residual stresses are found in weld joints because of the localized heat input, the difference between the expansion coefficients of joint members, and the restraints around the welded zones. In particular, high residual tensile stresses occur near welded zones. These stresses can affect the fracture and fatigue behaviors in welded structures1). Naturally, for assessing theses behaviors in detail, the inner residual stress fields are as important as surface residual stress fields. The neutron diffraction technique is a well-known evaluation method for the inner residual stress fields2). However, it is not always possible to easily conduct evaluations with this technique because it requires extensive experimental equipment and a stress-free sample. In addition, this technique cannot be applied to the residual stress evaluation of plates more than several tens of millimeters in thickness. Therefore, a new technique for evaluating inner residual stress fields is needed when the neutron diffraction technique cannot be applied.

Consequently, the deep hole drilling (DHD) technique has received much attention in recent years as a method for measuring through-thickness residual stresses3-5). The DHD technique measures the diametric change of a reference hole drilled thorough the component before and after the residual stress release. The residual stress release is performed by trepanning a column of material containing the reference hole. The DHD technique has some advantages over the neutron diffraction technique, such as simpler test devices and procedures, applicability to thick plates, and in-field testing capability. However, some accuracy problems occur with the DHD technique. One reason is that the traditional evaluation formula assumes that the stress condition around the reference hole is two-dimensional plane stress. Under this assumption, the stress conditions around the reference hole cannot be considered precisely. In addition, the effect of the residual stress distribution in thickness direction is ignored.

Therefore, this study proposes a new evaluation formula and procedure using three-dimensional stress functions to solve the accuracy problems and to evaluate the residual stress more accurately using the DHD technique. Then, a known stress field is evaluated by the traditional formula and the new formula using the finite element method (FEM) to compare the accuracy of the both results.

2. Diametric changes of the reference hole under the three-dimensional stress conditions

In this chapter, a new evaluation formula and procedure using three-dimensional stress functions are proposed. The effect of the stresses in thickness direction on the diametric changes, which are ignored in traditional evaluation formula, can be considered by using three-dimensional stress functions. First developed are the relationships between the uni-axial stress fields $\sigma(x)$ in the x direction, which have an arbitrary distribution in the z direction, and the diametric changes. The z direction is the thickness direction ($0<z<h$, $h$: thickness of object) and the x direction is the direction normal to the thickness direction as shown in Fig. 1. Here, $\sigma(z)$ can be expressed as a Fourier series...
The non-axisymmetric stress components are as follows: 

\[ h_1 = -4 \left( n_1 \rho_0 \frac{K_1(n_1 \rho_0)}{K_2(n_1 \rho_0)} + 3 \right), h_2 = n_1 \rho_0 \frac{K_1(n_1 \rho_0)}{K_2(n_1 \rho_0)} + 2, \]

\[ g_2 = 2(1 - v)n_1 \rho_0 \frac{K_1(n_1 \rho_0)}{K_2(n_1 \rho_0)} - (n_1 \rho_0)^2 + 2(1 - 2v), \]

\[ h_2 = -2, \quad f_2 = 2 \left( n_1 \rho_0 \frac{K_1(n_1 \rho_0)}{K_2(n_1 \rho_0)} + 3 \right), \]

\[ g_3 = -(n_1 \rho_0)^2, \quad h_3 = - \left( 2n_1 \rho_0 \frac{K_1(n_1 \rho_0)}{K_2(n_1 \rho_0)} + (n_1 \rho_0)^2 + 12 \right). \]

When \( F, G \) and \( H \) are determined by Eq. 2, the stress components in the thickness direction can also be determined.

\[
\frac{(\sigma_2)_{\zeta = \pm \pi}}{2\nu \rho_0^2 F_{1n_1} \cos 2\theta} =
\begin{bmatrix}
(-)^{n_1} K_2(n_1 \rho_0) \\
F - \left( n_1 \rho_0 \frac{K_1(n_1 \rho_0)}{K_2(n_1 \rho_0)} - 2(1 - v) \right) G
\end{bmatrix}
\]

\[
\begin{bmatrix}
(-)^{n_1} K_2(n_1 \rho_0) \\
F - \left( n_1 \rho_0 \frac{K_1(n_1 \rho_0)}{K_2(n_1 \rho_0)} - 2(1 - v) \right) G
\end{bmatrix}
\]

On the surface \( (\zeta = \pm \pi), \sigma_2 \) has to be zero. Therefore, the following additional stress functions are used.

[Stress function I]

\[ \sigma_2 = \frac{2\nu \rho_0^2 F_{1n_1} \cos 2\theta}{r^2} \cdot \Omega \log r \]

[Stress function II]

\[ \sigma_2 = \frac{2\nu \rho_0^2 F_{1n_1} \cos 2\theta}{r^2} \cdot \Omega \log r \]

[Stress function III]

\[ \sigma_2 = \frac{m E_m C_m \cos m \theta}{r^2} \cdot \Omega \log r \]

where, \( C_m(\theta) = F_0(\theta) - \left( \frac{1}{m} \frac{d}{d\theta} \right) F_0(\theta) \), is the Bessel function of the first kind of order \( \beta \), \( Y_m(\theta) \) is the Bessel function of the second kind of order \( \beta \). Here, \( m \) is the value that satisfies \( \frac{C_m(\alpha m)}{C_m(\beta m)} = 0 \) \( (\alpha \gg \beta) \), and \( m_1, m_2, m_3 \ldots \) are defined as the numbers of \( m \) in ascending order. The stresses, which are obtained by these functions, have to satisfy the following boundary conditions:

At \( r = \infty \), all stress components are zero.

At \( r = \alpha \), \( \sigma_2 = \tau_{\theta} = \tau_{rz} = 0 \).

At \( \zeta = \pm \pi, \tau_{\theta} = \tau_{rz} = 0 \),

\[
\frac{(\sigma_2)_{\zeta = \pm \pi}}{2\nu \rho_0^2 F_{1n_1} \cos 2\theta} =
\begin{bmatrix}
(-)^{n_1} K_2(n_1 \rho_0) \\
F - \left( n_1 \rho_0 \frac{K_1(n_1 \rho_0)}{K_2(n_1 \rho_0)} - 2(1 - v) \right) G
\end{bmatrix}
\]

Here, \( D_m \) is determined as \( E_m(1 - 2v - mn) \cot mn \),

\[-\left( -1 \right)^n K_2(\alpha_m) C_{\alpha_m} \]

is defined as \( 2\nu \rho_0^2 A_{1n_1} C_{\alpha_m} \)

and

\[
4m \sinh mn \cot mn k_m \]

is defined as \( 2\nu \rho_0^2 A_{1n_1} E_m \), the relationships of the coefficients obtained by the boundary condition on the hole surface \( (r = \alpha) \) are as follows:
where

\[ K_a = K_a(n_\rho_0), \quad a_1 = n_\rho_0 K_1 + (n_\rho_0)^2 + 6, \]
\[ a_2 = n_\rho_0 \frac{K_1}{K_2} + 2, \quad a_3 = 2 \left( n_\rho_0 \frac{K_1}{K_2} + 3 \right), \]
\[ \beta_1 = -\frac{(n_\rho_0)^2}{2} \left( \frac{K_1}{K_2} + 1 + 2 v \right), \]
\[ \beta_2 = 2(1 - v) n_\rho_0 \frac{K_1}{K_2} - (n_\rho_0)^2 + 2(1 - 2v), \]
\[ \gamma_3 = -\frac{(n_\rho_0)^2}{2} \left( \frac{K_1}{K_2} + 3 + 2 \right), \]
\[ \delta_{3n} = -2 \left( \frac{(n_\rho_0)^2}{2} + 2 + 6 \right), \]
\[ \delta_{2n} = -2 \left( \frac{(n_\rho_0)^2}{2} + 2 + 6 \right), \]
\[ \delta_{1n} = 1, \]
\[ \delta_{2n} = 0, \]
\[ \delta_{3n} = 1. \]

In addition, the relationships of the coefficients obtained by the boundary condition on the surface \( (\zeta = \pm \pi) \) are as follows:

\[
\frac{(a_2)_{\zeta = \pi}}{2v^2 p_{1n} \cos 2\theta} = - \frac{1}{\rho_0^2} (1 + v) \rho_0^2 n_\rho_0^2 \]
\[
+ \sum \frac{1}{2} \left[ A[K_2(n_\rho) - B(n_\rho K_1(n_\rho) - 2(1 - v))] \right] \frac{E}{m_\rho} \frac{m_\rho}{m_\rho m_\rho} \left( \sinh m_\rho \frac{m_\rho}{m_\rho m_\rho} \right) C_2(m_\rho) \]
\[
- \frac{1}{4} \sum E_m \frac{m_\rho}{m_\rho m_\rho} \left( \cosh m_\rho + \frac{m_\rho}{m_\rho m_\rho} \right) C_2(m_\rho) \]
\[
= (-n_\rho K_2(n_\rho) \frac{K_2(n_\rho)}{K_1(n_\rho)} \left[ f - \left( \frac{n_\rho K_1(n_\rho)}{K_2(n_\rho)} - 2(1 - v) \right) \right] G \]

and where, \( C_2 = \frac{C_0}{C_0} \). Now, \( K_2(n_\rho) \) and \( n_\rho K_1(n_\rho) \) are expanded in the Fourier-Bessel series

\[ K_2(n_\rho) = \frac{a_{on}}{2} \rho^2 + \sum b_{mn} C_2(m_\rho) \]
\[ n_\rho K_1(n_\rho) = \frac{b_{on}}{2} \rho^2 + \sum b_{mn} C_2(m_\rho) \]

where

\[ a_{on} = \frac{\rho_0^2 p_{2n}}{2} \left( \rho_0 K_1(n_\rho_0) + \rho_0 K_1(n_\rho_1) \right) \]
\[ a_{mn} = \frac{\rho_0^2 p_{2n}}{2} \left( \rho_0 K_1(n_\rho_2) + \rho_0 K_1(n_\rho_2) C_2(m_\rho) \right) \]
\[ b_{on} = \frac{2 \rho_0^2 p_{2n}}{2} \left( K_0(n_\rho_0) - K_0(n_\rho_1) \right), \]
\[ b_{mn} = \frac{2 \rho_0^2 p_{2n}}{2} \left( K_0(n_\rho_2) - K_0(n_\rho_2) C_2(m_\rho) \right) \]
\[ \times \left( 1 \right) \left( \rho_0 K_1(n_\rho_2) C_2(m_\rho) \right) \]
\[ \left( n_\rho K_1(n_\rho_2) C_2(m_\rho) \right) \left[ (n_\rho K_1(n_\rho_2) C_2(m_\rho) \right] \]
\[ \left( n_\rho K_1(n_\rho_2) C_2(m_\rho) \right) \]

and where, \( \rho_0 \gg \rho_0 \). Here, the coefficients of \( 1/\rho_0^2 \) and \( C_2(m_\rho) \) are to be zero in Eq. 3. Therefore, using Eq. 3 and Eq. 4:

\[
\sum d_{1n} E_z = f_0 + f_\rho E_\rho \sum d_{2n} E_z = f_\theta + f_\rho E_\rho \]

where

\[ f_0 = \left( -1 \right)^n \left( F a_{on} - G b_{on} \right), \]
\[ f_\theta = \left( -1 \right)^n \left( F a_{mn} - G b_{mn} \right), \]
\[ f_\rho = \frac{1}{2} \rho_0^2 \left( \frac{1}{4 \sinh m_\rho} \left( \cosh m_\rho + \frac{m_\rho}{m_\rho m_\rho} \right) \right) \]
\[ d_{s0} = \sum \left( g_{sm} a_{on} - g_{sm} b_{on} \right), \]
\[ d_{sm} = \sum \left( g_{sm} a_{mn} - g_{sm} b_{mn} \right), \]
\[ a_{on} = \frac{a_{on}}{K_2}, \]
\[ b_{on} = \frac{b_{on}}{K_2}, \]
\[ b_{mn} = \frac{b_{mn}}{K_2}, \]
\[ b_{mn} = \frac{b_{mn}}{2(1 - v) a_{mn}}. \]

Here, \( g_{sm}, a_{on} \) are the values that satisfy \( A_n = \sum \sum \cos E_z, B_n = \sum g_{sm} E_z \). Therefore, these are obtained from Eq. 3. Secondly, axisymmetric stress components are as follows:

\[ \sigma_\rho = \frac{1}{2} \sigma_{1n}, \quad \sigma_\theta = \frac{1}{2} \sigma_{1n}, \quad \sigma_\rho = \frac{1}{2} \sigma_{1n}. \]

In addition when \( K_1 \left( P', Q' \right) \) is defined as \( 2v \sigma_{1n} \left( P, Q \right) \), \( P \) and \( Q \) can be determined as

\[
\left( P\right) = \frac{p_1 q_1}{p_2 q_2} - \left( \frac{1}{4v} \right) \left( \frac{1}{0} \right)
\]

where

\[ p_1 = \frac{K_0}{K_1} \left( \frac{1}{n_\rho_0} \right), \quad q_1 = \left( -n_\rho_0 + (1 - 2v) \frac{K_0}{K_1} \right), \]
\[ p_2 = 2, \quad q_2 = 2(1 - v) - n_\rho_0 \frac{K_0}{K_1}. \]

When \( P \) and \( Q \) are determined by Eq. 5, the stress components in the thickness direction can also be determined.

\[
\left( \frac{\sigma_\rho}{\sigma_{1n}} \right)_{\zeta = \pm \pi} = \frac{(-1)^n}{n_\rho} \frac{K_0}{K_1} \left( \frac{p_0 \sigma_{1n}}{K_0} \right) \frac{K_0(n_\rho_1)}{K_1(n_\rho_1)} \left( \frac{p_0 \sigma_{1n}}{K_0} \right) \]
\[ \tau_{\rho \theta} = \tau_{\rho \theta} = 0. \]

On the surface \( (\zeta = \pm \pi) \), \( \sigma_\rho \) has to be zero. Therefore, the following additional stress functions are used. [Stress function I]

\[
2G\varphi_0 = \sum_{m=0}^{n} \sum_{n=0}^{m} \left( \frac{R_n^m}{n^2} \right) C_0(n_\rho \sin m_\rho) \cos m_\rho \]
\[ \left( \frac{2G\varphi_0}{2G\varphi_0} \right) \cos m_\rho \sin m_\rho \]

The stresses, which are obtained by these functions, have to satisfy the following boundary conditions:

At \( r = \infty \), all stress components are zero.

At \( r = a \), \( \sigma_\rho = \tau_{\rho \theta} = \tau_{\rho \theta} = 0. \]

At \( \zeta = \pm \pi \), \( \tau_{\rho \theta} = \tau_{\rho \theta} = 0. \]

\[
\left( \frac{\sigma_\rho}{\sigma_{1n}} \right)_{\zeta = \pm \pi} = \frac{(-1)^n}{n_\rho} \frac{K_0}{K_1} \left( \frac{p_0 \sigma_{1n}}{K_0} \right) \frac{K_0(n_\rho_1)}{K_1(n_\rho_1)} \left( \frac{p_0 \sigma_{1n}}{K_0} \right) \]
\[ \tau_{\rho \theta} = \tau_{\rho \theta} = 0. \]

Here, when \( T_m' \) is determined as \( U_m' \left( 1 - 2v - \frac{1}{m \pi \cot m_\rho} \right) \),
\( nK_1[R_n',S_n'] \) is defined as \( 2\nu\sigma_{1n}[R_n,S_n] \) and
\( 2m^2 \sinh \frac{m \pi r}{r_m} \frac{U_m'}{U_m} \) is defined as \( 2\nu\sigma_{1n}U_m \), the relationships of the coefficients obtained by the boundary condition on the hole surface \((r = a)\) are as follows:

\[
\begin{align*}
(r_1 \int \frac{u_1}{s_1} &= \left( \int_0^1 \delta_{1n} U_1 \right) (n = 1, 2, 3, \ldots) \\
(r_2 \int s_2 &= \left( \int_0^1 \delta_{1n} U_2 \right) (s = 0, m, m_2, \ldots)
\end{align*}
\]  (6)

where
\[
(r_1 = K_0 + \frac{1}{\nu_0}, s_1 = -\nu_0 + (1 - 2\nu) \frac{K_0}{K_1},
\]
\[
r_2 = -1, s_2 = 2(1 - 2\nu) - \nu_0 \frac{K_0}{K_1}, \delta_{1n} = -\frac{2n^2}{(s^2 + n^2)^{3/2}}.
\]

In addition, the relationships of the coefficients obtained by the boundary condition on the surface \((\xi = \pm \pi)\) are as follows:

\[
(\sigma_2)_{\xi = \pm \pi} = \left. \left[ \begin{array}{l l}
- & \sum_{m} \frac{C_0(m\rho)}{m \sinh \frac{m \pi \rho}{r_m}} \left[ \cos m \pi f + \frac{m \pi f}{\sinh m \pi f} \right] U_m \\
- & \sum_{m} \frac{C_0(m\rho)}{m \sinh \frac{m \pi \rho}{r_m}} \left[ \cos m \pi f + \frac{m \pi f}{\sinh m \pi f} \right] U_m
\end{array} \right] \right|_{\xi = \pm \pi} \]

\[
= \left. \left[ \begin{array}{l l}
- & \sum_{m} \frac{C_0(m\rho)}{m \sinh \frac{m \pi \rho}{r_m}} \left[ \cos m \pi f + \frac{m \pi f}{\sinh m \pi f} \right] U_m \\
- & \sum_{m} \frac{C_0(m\rho)}{m \sinh \frac{m \pi \rho}{r_m}} \left[ \cos m \pi f + \frac{m \pi f}{\sinh m \pi f} \right] U_m
\end{array} \right] \right|_{\xi = \pm \pi} \]

Now, \( K_0(\nu) \) and \( n\rho K_1(\nu) \) are expanded in the Fourier-Bessel series

\[
K_0(\nu) = \sum m a_{mn} C_0(m\rho), n\rho K_1(\nu) = \sum m b_{mn} C_0(m\rho)
\]

where

\[
a_{mn} = \frac{2n}{(m^2 + n^2)((2m^2 \pi^2) - C_0^2(m\rho_0) \pi^2)}
\]

\[
b_{mn} = \frac{2n}{(m^2 + n^2)((2m^2 \pi^2) - C_0^2(m\rho_0) \pi^2)}
\]

Now, the coefficients of \( C_0(m\rho) \) are to be zero in Eq. 7.

Therefore, using Eq. 6 and Eq. 7,

\[
\sum \delta_{1n} U_1 = f_m + f_m U_m
\]

where

\[
f_m = (-1)^n (PA_{mn}' + Qb_{mn}')
\]

\[
f_m = \frac{2m^2 \sinh \frac{m \pi r}{r_m} \left( \cos m \pi f + \frac{m \pi f}{\sinh m \pi f} \right)}{C_0}.$
\]

\[
\sum \delta_{1n} U_2 = f_m + f_m U_m
\]

\[
a_{mn}' = \frac{a_{mn}}{K_1}, b_{mn}' = \frac{(b_{mn}')}{K_1} 2(1 - 1) \frac{a_{mn}}{K_1}
\]

Here, \( a_{mn}', b_{mn}' \) are the values that satisfy \( R_n = \sum_n g_{mn} U_1 + S_n = \sum_n g_{mn} U_2 \). Therefore, these are obtained from Eq. 6.

The coefficients of each stress functions are determined uniquely according to the above discussion. Now, the displacement of the hole edge is determined as follows:

\[
- \frac{G}{\nu \sigma_{1n}} u_1 (x, \theta) + \frac{1}{n^2} \left( - \frac{n\rho_0}{K_1} \right) \left( 2n^2 \right) + \left( n\rho_0 \right)^2 B_n + 4C_n \cos n\zeta \cos 2\theta
\]

\[
\sum \frac{E_0 (x, \theta)}{m} \cos n\zeta = \sum \frac{v E_m}{m^2} - \frac{n\rho_0 + 2n^2}{12} \cos 2\theta
\]

\[
+ \left( \sum \frac{v E_m}{m^2} + \sum \frac{n\rho_0 + 2n^2}{m^2 + n^2} \cos n\zeta \right) \cos 2\theta
\]

\[
= - \frac{1}{n^2} \left( 2n^2 \right) \left( \frac{n\rho_0}{K_1} \left( K_1(n\rho_0) + 2 \right) \right) \cos n\zeta \cos 2\theta
\]

\[
= - \frac{4}{n^2} \left( \frac{n\rho_0}{K_1} \right) \left( K_1(n\rho_0) + 2 \right) \cos n\zeta \cos 2\theta
\]

\[
= - \frac{4}{n^2} \left( \frac{n\rho_0}{K_1} \right) \left( K_1(n\rho_0) + 2 \right) \cos n\zeta \cos 2\theta
\]

In addition, when the diametric changes caused by the uni-axial stress fields \( \sigma(z) \) are denoted by \( U_{\text{single}}(\sigma, z, \theta) \), the diametric changes caused by the multi-axial stress fields \( U_{\text{multi}}(\sigma_x, \sigma_y, \tau_{xy}, z, \theta) \) are written as follows:

\[
U_{\text{multi}}(\sigma_x, \sigma_y, \tau_{xy}, z, \theta) = U_{\text{single}}(\sigma_x, z, \theta + \pi) + U_{\text{single}}(\tau_{xy}, z, \theta + \pi)
\]

When Eq. 8 is applied to the residual stress evaluation using the DHD technique, the residual stress fields are the stress fields that satisfy Eq. 8 using \( U_{\text{multi}} \) obtained by the DHD process.

3. Method for evaluating residual stress considering three-dimensional stress fields

The diametric changes can be calculated from the residual stress fields by using Eq. 8. Therefore, the residual stress fields can be calculated from the diametric changes obtained by the DHD procedure as follows:

1. Calculate \( (\sigma_x), (\sigma_y), (\tau_{xy}) \) from the diametric changes \( U \) by using Eq. 9.

2. Calculate \( U_{\text{multi}} \) from \( (\sigma_x), (\sigma_y), (\tau_{xy}) \) by using Eq. 8.

3. Calculate the differences between \( \Delta U (U - U_{\text{multi}}) \).

4. Calculate \( \Delta \sigma_x, \Delta \sigma_y, \Delta \tau_{xy} \) by using Eq. 10.

5. Calculate \( U_{\text{multi}} + \Delta \sigma_x, \Delta \sigma_y, \Delta \tau_{xy} \) from \( U_{\text{multi}} + \Delta \sigma_x, \Delta \sigma_y, \Delta \tau_{xy} \).

6. When \( \Delta U > \kappa \) (\( \kappa \): convergence criteria), go back to 3.

Afterwards, \( i \) is replaced to \( i + 1 \).

\[
U(z, \theta) = - \frac{1}{E} \left( \sigma_x (1 + 2 \cos 2\theta) + \sigma_y (1 - \cos 2\theta) + \tau_{xy} (4 \sin 2\theta) \right)
\]

\[
\Delta U(z, \theta) = - \frac{1}{E} \left( \Delta \sigma_x (1 + 2 \cos 2\theta) + \Delta \sigma_y (1 - \cos 2\theta) + \Delta \tau_{xy} (4 \sin 2\theta) \right)
\]
4. Evaluation of a residual field by proposed and traditional formulae

The object used for the FEM is shown in Fig. 2. The initial diameter of the reference hole is 2 mm, and the outside diameter of the trepanned cylinder is 4 mm. The size of the mesh in the radial direction around the reference hole is approximately 0.03 mm. The thickness is divided into 1000 meshes and the arc is divided into 144 meshes. In this analysis, the object is assumed to have an elastic body (Young’s modulus: 200 GPa, Poisson’s ratio: 0.3) and the residual stress is applied in the x direction. The distribution is represented by a quadratic function that has maximum values at the surfaces of the object and a minimum value at the middle of the object. The absolute values of these values are 300 MPa. The diametric changes for the residual stress evaluation are obtained at the angles of 0°, 45° and 90° by using the result of the FEM as shown in Fig. 2. In the evaluation by the traditional and the proposed formulae (Eq. 8), $\sigma_y$ and $\sigma_{xy}$ are not fixed to zero. The evaluation results obtained by both formulae and the applied stress are shown in Fig. 4. The errors of both evaluation results, which are calculated by $(\text{Applied stress}) - (\text{Evaluated stress})$, are shown in Fig. 5. These results indicate that the proposed formula can evaluate the residual stress better than the traditional formula can.

5. Conclusions

A new evaluation formula that considers the effects of the three-dimensional stress condition was presented. The evaluation results obtained by the proposed formula agree with the applied stress better than those obtained by the traditional formula. Using the proposed formula, the DHD technique can evaluate residual stresses more accurately.

Reference