Evaluation of weld residual stress field by the deep hole drilling technique based on three-dimensional elasto-plasticity theory*

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In order to assess the applicability of the 3DP-DHD technique, which could consider the effects of threedimensional nature and plastic deformation around reference hole, as the measuring method of welding residual stress, the technique was applied to measurement of residual stress in multi-pass weld joint. In addition, evaluation results were compared with those obtained by the stress relief technique and finite element analysis. As a result, evaluation results obtained by the 3DP-DHD technique were in good agreement with those of other techniques generally.

Key Words: Deep hole drilling technique, weld residual stress, multi-pass weld joint

1. Introduction

The deep hole drilling technique (DHD) have been received attention as a method for measuring through-thickness residual stresses. The DHD technique has some advantages over the other techniques, such as simpler test devices and procedures, applicability to thick plates and in-field testing capability. Therefore, this technique is expected to apply for evaluating residual stresses in many structures. However, some accuracy problems can occur when residual stress evaluation is performed by the technique because the technique do not consider the effects of three-dimensional nature and plastic deformation around the reference hole precisely. Therefore, the new theory, which is called by the 3DP-DHD technique, have been developed by considering the effects of three-dimensional nature and plastic deformation for accurate evaluation in our works1-2). This technique can evaluate all components of residual stress fields accurately. In this study, the new theory is applied to evaluate the multi-pass weld joint whose residual stress distribution is expected to be complex. In addition, evaluation results are compared with the residual stress evaluation results obtained by the saw cutting technique proposed by E. Takahashi et. al.3) and the finite element (FE) analysis.

2. Measurement procedure of the 3DP-DHD technique

The 3DP-DHD technique is performed by the following procedure as shown in Fig. 1.

Step 1 A reference hole is drilled through the specimen with a gun drill (Drilling process).

Step 2 The diameters of the hole at several depths and angles and the initial height of the top of the hole are measured.

Step 3 A column of material containing the reference hole as its axis is coaxially freed (Trepanning process).

Step 4 The diameters of the reference hole and the height and lean of the top of the cylinder (trepanned core) are measured. Here, the trepanning is progressed inch by inch for measuring changing history of height and lean of the trepanned core in Step 3. Namely, Step 3 and Step 4 are performed alternately. As a result, elongation history \(l(L)\) and tilt history \(x(L), y(L)\) of cylinder and diametric change history \(d(\theta, z, L)\) with the trepanning process are measured (See Fig. 2). Here \(L\) is the trepanning depth as shown in Fig. 2. Then, these deformation histories are used for evaluating residual stress fields. The detailed procedure for evaluating residual stress fields in x-y plane \(\sigma_x, \sigma_y, \sigma_{xy}\) is shown in an early work. \(\sigma_z\) is calculated by following formula developed by the elastic solution.

\[
l_n = \frac{(\sigma_2)_n}{E} (z_n - z_{n-1}) + \int_{l_0}^{l_n} \frac{4y}{B(x)} \frac{\partial B}{\partial x} dx + 2(1 - \nu) \left( (\sigma_x)_n - (\sigma_x)_{n-1} \right) \frac{\pi^2 G(R_1^2 - R_0^2)}{\pi^2 G(R_1^2 - R_0^2)} \int_{R_0}^{R_1} \left( R_2 P \left( \frac{r}{R_2} \right) \right) - R_1 P \left( \frac{r}{R_1} \right) \right] 2\pi r dr
\]

where \(l_n\): elongation of the cylinder by \(n\)th trepanning step,
3. Residual stress evaluation of multi-pass weld joint by the FE analysis, the saw cutting technique and the 3DP-DHD technique

3.1 Preparation of measuring object

The measuring object is shown in Fig. 5(a). Here, the bottom side, which is made of SM490, is used as the constrained plate. Therefore, the residual stresses are evaluated only in the upper side. Figs. 5(b) and 5(c) show the groove shape and positions of bead passes. In each welding processes, arc current is 180–200 A, arc voltage is 11–12 V, welding speed is 8 cm/min. Argon gas is used as shielded gas. Flow rate of the gas is 15 l/min. Residual stresses are measured at the center of object as shown in Fig. 5(a).

3.2 The FE analysis condition

Figure 6 shows the object used for analysis. Only the measuring object (SUS304 part) is modeled. The plane strain condition is applied. The material properties used for the analysis are shown in Fig. 7. Here, density, thermal expansion coefficient and Poisson’s ratio are \( 7.96 \times 10^{-6} \) kg/mm\(^3\), \( 1.795 \times 10^{-5} \) 1/°C and 0.3 respectively at all temperature. These properties are that of SUS304. Under these condition, the thermal elastic-plastic analysis is performed. In the analysis, each welding passes are heated to 2000 °C and cooled naturally. The measurement line is also shown in Fig. 6.
3.3 Measurement procedure of the saw cutting technique

The saw cutting technique for measuring inner residual stresses was proposed by E. Takahashi et. al. For the technique, two specimens which are made by same condition have to be prepared. Then, by using the two specimens, the residual stress of measuring object is measured by following procedure;
1. Strain gages (Gauge length: 1 mm) are attached to the front and back side of the specimen as shown in Fig. 8.
2. Specimen are cut (20 mm width). One plate is cut in the longitudinal direction to the weld line. Another one is cut in the transverse direction to the weld line (See Fig. 8).
3. Strain caused by previous step is measured.
4. Strain gages are attached to the side surface as shown in Fig. 9.
5. plates, which made in Step 2 are cut (See Fig. 9).
6. Strain caused by previous step is measured.

Residual stress is calculated by using measured strain obtained by Step 2 and 6. The evaluation formula is shown in previous paper.
3.4 Measurement procedure of the 3DP-DHD technique

The 3DP-DHD technique is applied to the center of the specimen. The procedure is shown in chapter 2. Here, the initial diameter of the reference hole is 6 mm. Wall thickness of the cylinder is 3 mm. The drilling of the reference hole is performed by using the gun drill. The trepanning is performed by using the endmill.

3.5 Measurement results of deformation history in the 3DP-DHD technique

Figure 10 shows the measurement results of each deformation history in the trepanning process. Here, Fig. 10(a) shows diametric change history at the depth of 10 mm from surface as an example. As shown these figures, diameter, elongation and tilt are changed in the trepanning process. This is because the residual stresses around reference hole are released by the trepanning.

3.6 Residual stress evaluation results

Residual stress evaluation results obtained by all techniques are shown in Fig. 11. Here, the saw cutting technique can only $\sigma_x$ and $\sigma_y$. These results indicate that the 3DP-DHD technique can evaluate all components of residual stress field in thick plate experimentally. In addition, the results obtained by the 3DP-DHD technique are in rough agreement with those obtained by other techniques while the residual stress measurement area in the three techniques is not strictly equal. Especially, the results of $\sigma_y$ obtained by the 3DP-DHD technique is in good agreement with those obtained by FE analysis more than those obtained by the saw cutting technique. The results of $\sigma_x$ obtained by the 3DP-DHD technique around the front and back side different from those obtained by the other techniques. This is likely to be caused by simplified modeling of reinforcement in FE analysis and be caused by ill-finished surface of the reference hole around the front and back side, which is caused by vibration of a drill. Therefore, more detailed investigation is needed for the precise measurement in these region as a future work. The absolute values of $\sigma_x$ obtained the 3DP-DHD technique different from those obtained by FE analysis while distribution is in rough agreement with that obtained by FE analysis. This is likely to be caused by moving of specimen, which is caused by the trepanning machining. Therefore, there is a room for improvement of fixation method of specimen.

4. Conclusions

The 3DP-DHD technique, which could consider the effects of three-dimensional nature and plastic deformation around reference hole, was applied to residual stress evaluation of multi-pass thick plate. As a result, the technique could all components of residual stress field in the multi-pass weld joint and the evaluation results were in agreement with those obtained by other techniques.
Reference


Fig. 11  Residual stress measurement results.