Comparison of Measured Residual Stress in an Extra Thick Multi-pass Weld Using Neutron Diffraction Method and Inherent Strain Method

JeongUng Park[a*], GyuBaek An[b*], Wan Chuck Woo[c]

[a] Department of civil Engineering, Chosun University, Gwangu 501-759, Republic of Korea
[b] POSCO Technical Research Laboratories, Pohang, 790-785, Republic of Korea
[c] Neutron Science Division, Korea Atomic Energy Research Institute, Daejeon 305-353, Republic of Korea

ABSTRACT

Residual stresses existing in a multi-pass butt joint with a thickness of 70mm, using a flux-cored arc welding process, were measured by an inherent strain method (ISM). Since such a thick plate before welding contains a large amount of initial residual stresses (-300 to +100 MPa), the initial stresses were integrated with conventional ISM in order to determine the total residual stresses in a welded joint which is here named as integrated ISM. The integrated ISM has an initial stress integrated ISM and an initial inherent strain integrated ISM for the consideration of the initial stress distributions through the thickness of base plates. The results show that there is a significant difference between the integrated ISM with initial stresses or initial inherent strain and the conventional ISM without initial stresses. The residual stresses measured by any of the initial stress integrated ISM and initial inherent strain integrated ISM agreed well with the neutron diffraction measurement. Thus, the proposed integrated ISM is a proper destructive measurement method in the case of thick weld joints.

Keywords: welding residual stress, initial stress, measurement, inherent strain method, neutron diffraction

1. Introduction

With the increase of large-scale containership, a large amount of high-strength steels with extra thick plates is being extensively used. The welding stress existing in the extra thick welded plates has a significant effect on the integrity of the component in terms of brittle fracture and fatigue behavior. It has been reported that welding residual stress distribution in an extra thick plate can affect the propagation path of the crack [1]. Therefore, it is important to measure the distribution of welding residual stresses for the reliable design of the welded structures [2, 3]. So far various researches have been carried out for the determination of residual stresses on the surface of steels. However, it has been recently recognized that the internal residual stress distributions in welded joints are an important factor affecting the fatigue and brittle fracture of the structures [4]. Thus, the measurement of the internal residual stresses is important for structure assessments.

In this paper, the total residual stresses in the 70 mm thick multipass FACW butt joint were measured by integrating initial stress into ISM. Concretely, two methods named as initial stress integrated ISM and initial inherent strain integrated ISM were employed to determine the total residual stresses. Furthermore, the distributions of residual stresses were compared with the results of the Neutron Diffraction Method(NDM).

2. Inherent Strain Method

Generally, inherent strain produced by welding exists near the welded zone. Inherent strain is classified into two types; i.e., i) ineffective inherent strain, which causes deformation but does not generate the residual stress, and ii) effective inherent strain (hereinafter referred as “inherent strain”) which induces both residual stress and deformation.

If the inherent strain distribution is expressed by the values in finite elements [5], the relationship between inherent strain $\{\varepsilon^*\}$ and elastic strain $\{\varepsilon^e\}$ is given by Equation 1, which is available to any type of multi-pass thick welds and single pass thin plate welds [6].

$$\{\varepsilon^e\} = [H^*]\{\varepsilon^*\} \qquad (1)$$

Here, $\{\varepsilon^e\}$ is elastic strains, $\{\varepsilon^*\}$ is inherent strains, and $[H^*]$ is elastic response matrix.

The $[H^*]$ can be generated by performing elastic FE analysis on a welded joint or thin specimens cut from the welded joint [6]. Also, the relationship between stress $\{\sigma\}$ and inherent strain $\{\varepsilon^*\}$ can be derived.

$$\{\sigma\} = [D]\{\varepsilon^e\} = [D][H^*]\{\varepsilon^*\} \qquad (2)$$

Here, $\{\sigma\}$ is stress and [D] is elastic stress-strain matrix

3. Experiment

Figure 1 shows the dimension of butt joint with 61 welded passes and 21 layers using FCAW. Two plates with a dimension of 600 mm in length, 600 mm in width, and 70 mm in thickness were prepared and welded. The base steel was a kind of high-tensile steel for shipbuilding and its yield strength was 430MPa. The mechanical properties of base steel and the welding conditions are summarized in Tables 1 and 2, respectively. Figure 2 shows a macro-section of the multi-pass butt joint of 70 mm-thick plates by flux cored arc welding (FCAW). Meanwhile, to compare the residual stresses measured by integrated ISM with those measured by neutron diffraction method in which specimen dimension has some limitation, the residual stress measurement using both methods was performed on a cut-off joint with 300mm in width as shown in Fig.1. Furthermore, in order to eliminate the edge effect, the measurement and evaluation for the welding residual stress with consideration of initial stresses were carried out at the middle transverse section of a cut-off joint with 300mm long in the welding direction.

Table 1 Mechanical properties of the base steel specimen

Material	E(MPa)	υ	YP(MPa)	TS(MPa)	EL(%)
EH40-TMCP	219000	0.28	430	540	21

Table 2 Welding conditions and consumables

Welding consumables	Current	Voltage	Speed	Heat input
SF-36E (NSSW)	255A	32V	30 mm/s	17kJ/cm

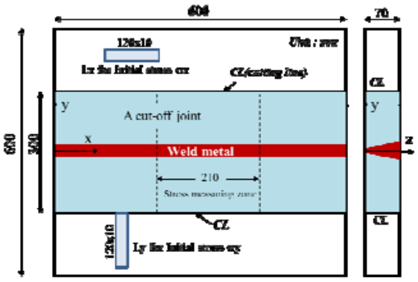

Figure 1 Dimension of the original welded joint, a cut-off joint for residual stress measurement and specimens (Lx, Ly) for initial stress measurement

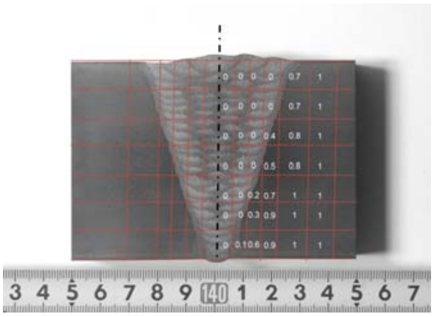

Figure 2 Through thickness macro-section and values of influencing factor α of initial stress

4. Results and Discussions

Figure 3 shows the distributions of welding residual stress (σ_x) along the welding direction (x) through thickness at 0 mm from welding centerline obtained by the inherent strain method. The marks ◆, ●, ▲ in Figure 3 are the residual stresses obtained when (i) there is no initial stress considered, (ii) initial stress integrated ISM and initial inherent strain integrated ISM (M2), and (iii) Neutron Diffraction Method is used. Note that the residual stress measured by neutron diffraction method shown in Figure 3(a) is the value at 0 mm (centerline) of the weld. The results (◆) in the weld metal, as shown in Figure 3(a) without consideration of the initial stress, are matched well with those measured using other methods. However, the results (◆) in the zones apart from the welding zone (30-100 mm), as shown in Figures 3(b)-(d) were entirely different from those by other measurement cases. It suggested that initial stress should be exactly evaluated and included into the inherent strain method.

The measured residual stresses (σ_x) near the welding zone were tensile in all the cases. On the contrary, as measurement points were apart from welding zone, residual stresses were strongly affected by initial residual stress. As a result, residual stress was compressive near two surfaces and tensile stress was present inside of the thickness. There were no significant differences in the results using initial stress integrated ISM and initial inherent strain integrated ISM. Although the overall distribution of residual stress measured by NDM and by integrated ISM matched well, the residual stress measured by neutron diffraction method was a little higher at y=60mm in Figure 3(c). One reason was that the residual stress measured by ISM was the average stress in a 10x10x10mm small piece which was much larger than evaluating size where the residual stress was measured by NDM. Of course, measurement errors were included in both measuring methods.

Figure 4 shows the welding residual stress distributions along the width direction (y) measured by inherent strain method. Residual stresses through the thickness of the plate were compared (i) without considering the initial stress, (ii) initial stress integrated ISM and initial inherent strain integrated ISM (M2), and (iii) using the Neutron Diffraction Method. The residual stresses measured at y=0, 30, 60, and 100 mm from the weld centerline showed almost similar results in all models. For example, the compressive residual stress generated inside through thickness and tensile residual stress was produced near the surfaces at y=0 and 30 mm as shown in Figures 4(a)-(b). Compared to the residual stress distribution at y=0 and 30mm near weld centerline, an opposite distribution of residual stresses was observed at y=60 and 100mm away from the welded zone which is shown in Figures 4(c)-(d). This is due to the influence of initial stress. From the results above, it is clear that the initial stress integrated ISM and initial inherent strain integrated ISM presented the effect of initial residual stresses well. Further, the results by neutron diffraction method were well-matched with the inherent strain method. Thus, it is suggested that the inherent strain method is reliable and represents appropriately the distributions of the residual stresses through the thickness of the thick weld plate.

5. Conclusion

In order to measure the three dimensional residual stresses in the welded joint with initial stresses existing before welding, initial stress integrated ISM and initial inherent strain integrated ISM were developed. The residual stresses in 70 mm-thick butt joint by flux cored arc welding were carried out with a good accuracy using the two developed methods. The residual stresses in welded joint using both initial stress integrated ISM and initial inherent strain integrated ISM agreed well with the results measured by Neutron Diffraction Method. This suggests that the integrated ISM is a reliable method for residual stress measurement if initial stress existed.

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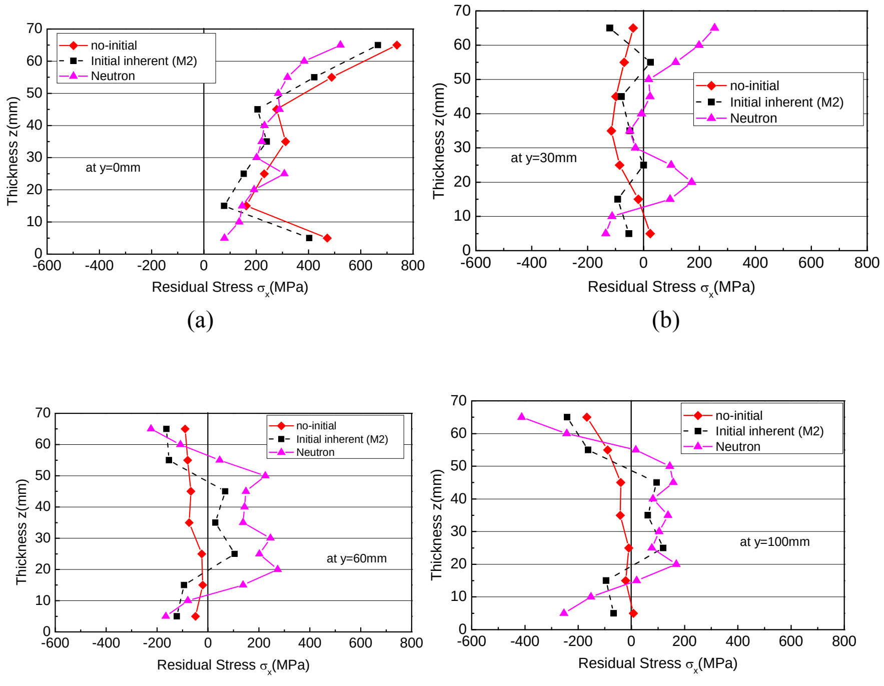

(a) (b)

(c) (d)

Figure 3 Through thickness distribution of residual stress (σx) at different y coordinate: (a) y=0mm, (b) y=30mm, (c) y=60mm, and (d) y=100mm at x=150mm and z=all

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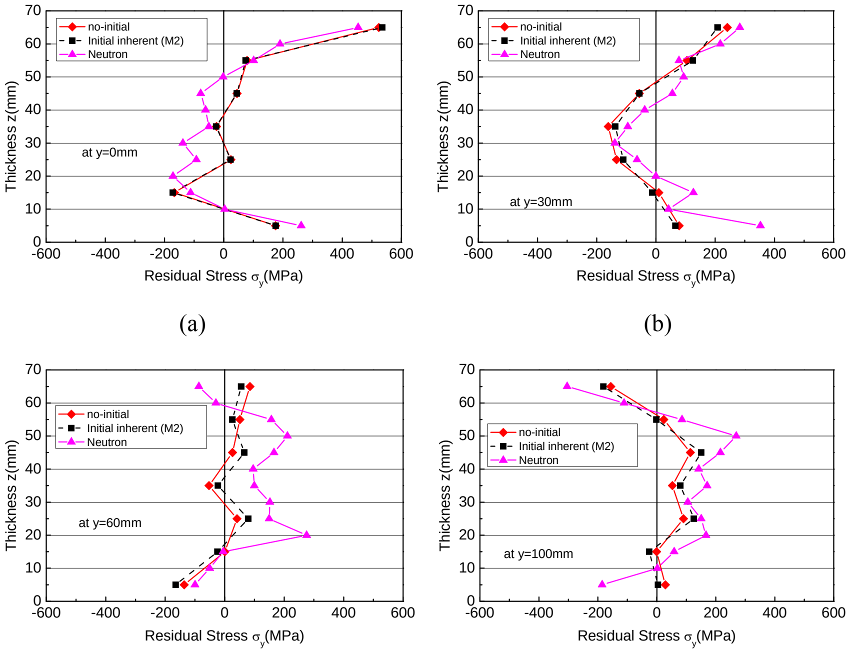

(a) (b)

(c) (d)

Figure 4 Through thickness distribution of residual stresses (σ_y) at different y coordinate: (a) y=0mm, (b) y=30mm, (c) y=60mm, and (d) y=100mm at x=150mm and z=all