Research Paper

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Numerical analysis on the welding residual stress and fracture toughness of the heavy thick steel welded joints by welding processes

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Abstract

This study examined the welding residual stress and fracture toughness of 78mm thick steel electro gas welding (EGW) and flux cored arc welding (FCAW) welded joints by numerical analyses of the thermal elasto-plastic behavior and fracture toughness(KIC). The residual stress, fracture toughness characteristics and production mechanism on the welded joints were clarified. Moreover, the effects of the welding process (EGW and FCAW) on the welding residual stresses and fracture toughness of welded joints were evaluated. The results showed that the new welding process (EGW) appears to be an effective substitute for the existing welding process (FCAW) in a thick steel plate with high strength.

Key Words : Heavy thick steel; Electro gas welding (EGW); Flux cored arc welding (FCAW); Welding residual stress; Fracture toughness

1. Introduction

To improve the economical benefit in the initial investment and working operation, ships have become larger than conventional types, particularly in container ships [1-3]. Along with this trend, such as container ships above 8000TEU, the use of high strength (>355N/mm^2) and thick steel plates EH36/EH40 (>70mm) in the construction of large sized ships has increased rapidly to satisfy the reduction of weight and increase the longitudinal strength of ships[4-7]. The application of these ultra thick steel plates, however, place high demand on the workload for welding. Therefore, the necessities of a high efficient manufacturing processes in welding, such as one pole EGW(Electro Gas Welding) for 55mm below in thickness, and two pole EGW or one pole & FCAW(Flux Cored Arc Welding) for 55mm above in thickness, were increased to overcome the difficulties with the conventional multi-layer welding process, such as semi-automatic arc welding, FCAW[8-13]. As EGW, which is an automatic welding for time saving, is a welding process with large heat input, the mechanical properties of welding consumable and base metal can be affected by potential brittle fracture. Furthermore, the crack susceptibility might be increased compared to the ordinary multi-layer welding process. Therefore, these thick steel plates, which are welded by large heat input, need to be treated by a post heat treatment at a controlled heat input to prevent further brittle fracture at the service stage[8-13]. Acknowledging these deteriorations in fracture toughness and fatigue life on high strength ultra thick steel plates, which have been used in large-sized welding constructions, some classification societies are considering the relevant requirements to estimate and reinforce the fracture toughness of a construction.

Owing to the intense concentration of heat during welding, the weld line and its vicinity undergo severe thermal cycles, which cause non-uniform heating and cooling of the material, thereby generating inhomogeneous plastic deformation and residual stress in the joint. The presence of welding residual stress can be detrimental to the performance of the welded product. For example, the tensile residual stress in the weld zone has been identified as a significant factor for reducing the resistance of the welded structure that contributes to the promotion of crack propagation and degradation of fatigue strength. Therefore, it is extremely important to understand the distribution of the welding residual stress and fracture mechanical phenomenon considering the welding residual stress to facilitate the structural design and life evaluation of welded structures. In this study, FEM analyses of the unsteady heat conduction and thermal elasto-plastic behaviors was carried out to clarify the welding residual stress and plain strain fracture toughness(K_{IC}) in the welded joints of high strength thick steel by the welding processes, EGW and FCAW, and further analysis of plain strain fracture toughness(K_{IC}) was performed considering the residual stress. Moreover, a comparative study was carried out on the welds for both EGW and FCAW welded joints.

2. Research Method

2.1 FE model and welding condition

In this study, shipbuilding steel plate, EH36-TMCP (classification grade) as a FE model, which is used in large container ships, was used to analyze large heat input welding(EGW), and existing multi-layer welding(FCAW). Tables 1 and 2 lists the chemical composition and mechanical properties of the EH36-TMCP and welding electrodes in accordance with the WPQT (Welding Procedure Qualification Test) of classification societies. The dimensions were 1,200mm in length, 400mm in breadth and 78mm in thickness. The shape and angle of the welding groove were chosen as an X shape in both sides, 30° in bevel angle and an 8mm gap, to reflect the field conditions of welding. Fig. 1, Table 3 and Table 4 provide details of the welding joint shape, number of layers and other welding condition, respectively. The FE model and mesh were determined to consider the temperature distribution and stress variation, as shown on Fig. 2, and an initial notch in accordance with BS 7448 was inserted into the CGHAZ (Coarsened

Table 1 Chemical compositions in EH36-TMCP and wire (Wt%)

Material	C	Si	Mn	P	S	Ni	Cu	Ti
EH36-TMCP	0.18	0.1~0.5	0.9~1.6	0.035	0.035	0.4	0.35	0.02
Wire for EGW	0.05	0.25	1.6	0.009	0.007	1.4	-	0.05
Wire for FCAW	0.04	0.38	1.10	0.012	0.010	1.55	-	-

Table 2 Mechanical properties of EH36-TMCP and wire (Wt%)

Material	Y.S(N/mm^2)	T.S(N/mm^2)	E.I(%)
EH36-TMCP	355	490~620	21
Wire for EGW	500	615	25
Wire for FCAW	560	620	29

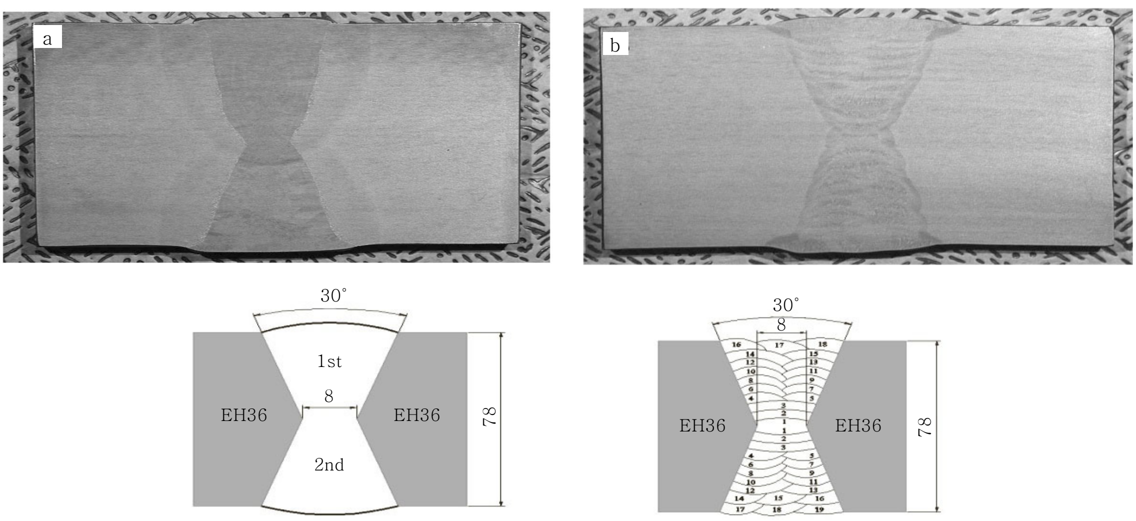


Fig. 1 Details of welding joint shape and number of layer

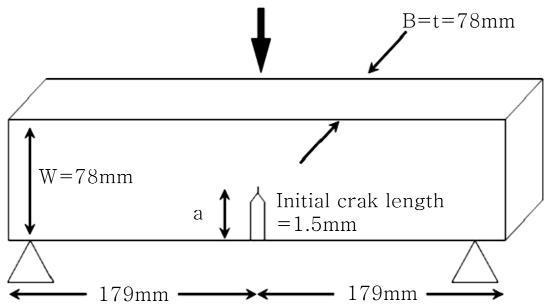
Grain Heat Affected Zone) adjacent to the fusion line to estimate the quantitative toughness value around the fusion line.

Table 3 Welding condition for EGW

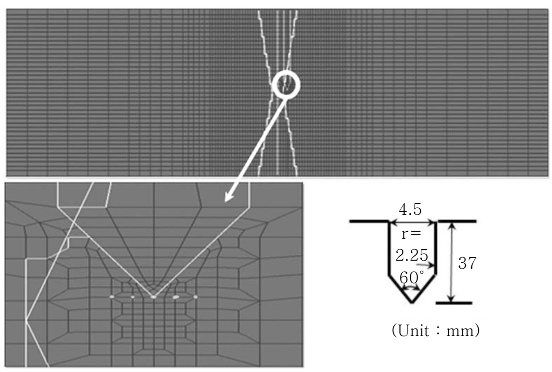
Process	Number of Pass	Current (A)	Voltage(V)	Arc Time(sec)
EGW (3G)	Top (1Pass)	400	42	1589
		Speed (cm/min)	Interpass Temp (℃)	Heat Input (KJ/cm)
		4.5	116	235.2
	Bottom (1Pass)	Current (A)	Voltage(V)	Arc Time (sec)
		430	44	1310
		Speed (cm/min)	Interpass Temp (℃)	Heat Input (KJ/cm)
		5.5	162	206.4

Table 4 Welding condition for FCAW

Process	Number of Pass	Current (A)	Voltage (V)	Arc Time (Sec)	Interpass Temp(℃)
FCAW	Top (18Passes)	240~300	29~31	153~405	119~152
	Bottom (19Passes)	275~300	31~32	176~373	111~157



(a) Dimension of specimen



(b) FE model

Fig. 2 Dimension of specimen and FE model

2.2 Analysis method

In this study, the following three procedures for welding heat conduct, residual stress and fracture analysis were carried out to examine the fracture toughness, K_{IC}, for a high strength ultra thick plate (EH36-TMCP) by each welding process, EGW and FCAW[14-20]:

1) Analysis of heat conduct: Temperature distribution with time
2) Analysis of the welding residual stress: Thermal stress, residual stress and strain by the uneven temperature distribution
3) Analysis of the fracture behavior: Plain strain fracture behavior by the residual stress superposed with an external load

Unsteady state heat conduction and 2-D(two-dimensional) plane deformation thermal elastic-plastic analysis were carried out. Based on the results, to validate the numerical analysis result, X-ray diffraction was performed to examine the residual stress of the welded joints, and the results were compared with those of numerical analysis. The distribution of residual stress along the parallel to the weld zone in the weld was analyzed at approximately 1 mm below the top surface and bottom of the weld specimen. A total of 370 points with a distance of 2, 3, 6, 18mm from the end of the welding bead were measured. FEM analysis of the fracture toughness, K_{IC}, for the welding region, where a bending force and the superposition with the bending and existing residual stress have been applied, were considered to predict the fracture toughness by each welding process, EGW and FCAW, according to the change in a/W. In accordance with BS 7448, the FE model was chosen to be same as the condition of the 3 point bending experiment. When external bending load was applied to the specimen, which was reflected the notch and initial crack on CGHAZ, the stress intensity factor at the initial fracture point was analyzed to the specimen.

The crack-initiation point P_Q was calculated from the load-clip gauge displacement curve, which was obtained from the 3 point bending experiment. The stress intensity factor K_Q was calculated based on the calculated P_Q as a crack-initiation point and after an assessment of the validity of K_Q, as described on (1), K_Q was considered to be K_{IC} as the plain strain fracture toughness.:

$$B,\ \alpha \geq 2.5(K_Q/\sigma_y)^2 \qquad (1)$$

The fracture toughness of the welding region was predicted according to the change in welding process. The load P_Q at the crack-initiation point was calculated from Ps, which has crossed between the OA', less than 5%

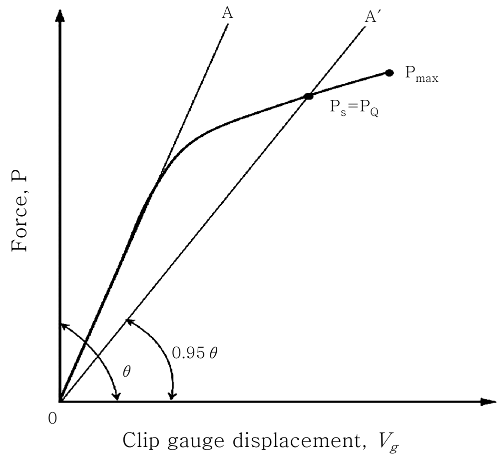


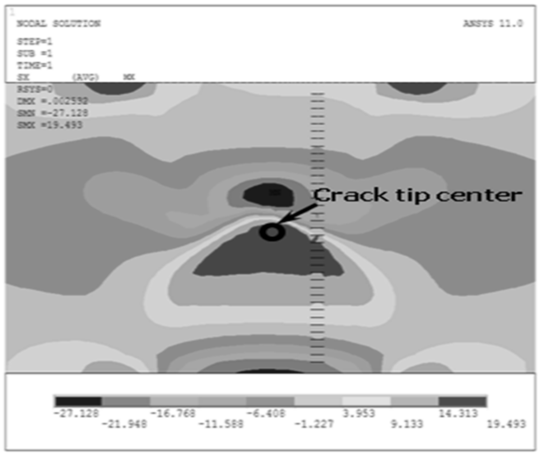
Fig. 3 Definition of P_Q load at the crack-initiation point

from the liner gradient OA, and Ps on the load-clip gauge displacement curve as shown in Fig. 3. The load P_Q at the crack-initiation point in EGW and FCAW was 13,700Kgf and 13,900Kgf, respectively, when only a bending load was applied without welding residual stress. When the bending load and welding residual stress were applied, the loads to the crack-initiation point P_Q were 12,500Kgf and 13,000Kgf in the EGW and FCAW, respectively.

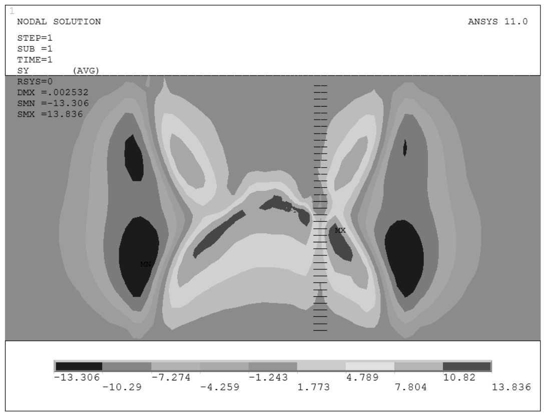
3. Results and Discussions

3.1 Comparison of the residual stress in EGW and FCAW welded joints

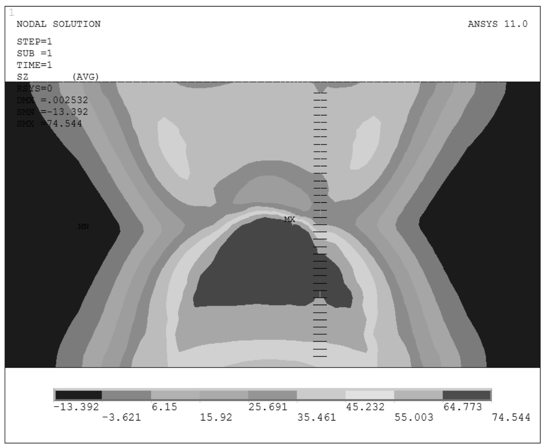
The effects of the welding residual stress on the fracture behavior through the crack tip were examined by considering the characteristics of the distributed welding residual stress via the crack tip in the EGW and FCAW welded joints. Fig. 4 shows the welding residual stress profiles obtained from two dimensional plane deformation thermal elasto-plastic analysis on the EGW welded joints. The results showed that the magnitude of each welding residual stresses was in the following order: the welding residual stress in welding line direction, $σ_{zz}$ > welding residual stress in width direction, $σ_{xx}$ > welding residual stress in thickness direction $σ_{yy}$. This result was caused by difference in mechanical restraints. An examination of the welding residual stress showed that tensile $σ_{zz}$, compressive $σ_{xx}$ and $σ_{yy}$ occurred on the front side weld and a large amount of compressive σxx was distributed at the center part of the specimen. In the case of backward welding, all stress components in the weld metal region showed tensile stress, particularly in the center part of the specimen. Moreover, the large $σ_{zz}$, appeared to exceed the yield stress compared to that of the front welding due to the restraint by the former deposited welding i.e. front side welding. The maximum stress $σ_{zz}$, produced on the center layer of thickness direction was caused by high restraint, which was concentrated on the center layer due to the welding heat input.



(a) $σ_{xx}$



(b) $σ_{yy}$

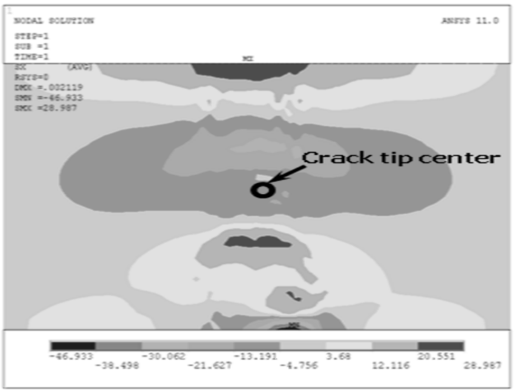


(c) $σ_{zz}$

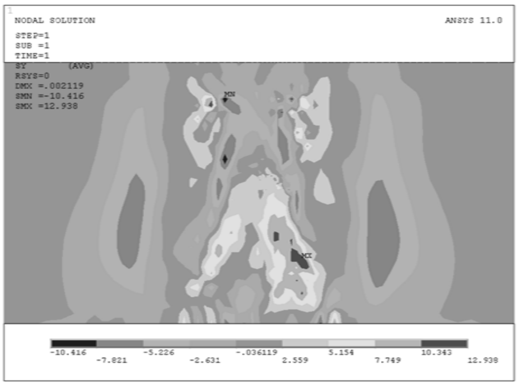
Fig. 4 Welding residual stress profiles on the EGW welded joints

To examine the effects of the welding residual stress to fracture behavior via the crack tip, the characteristics of the distributed welding residual stress via the crack tip in the EGW welded joints were investigated. A review of the welding residual stress in the width direction, which will exert fracture behavior, such as crack opening-closure on the crack tip, the tensile stress related to crack opening occurred on the crack tip. Therefore, this tensile stress can seriously affect crack opening, even crack propagation, without a further external load.

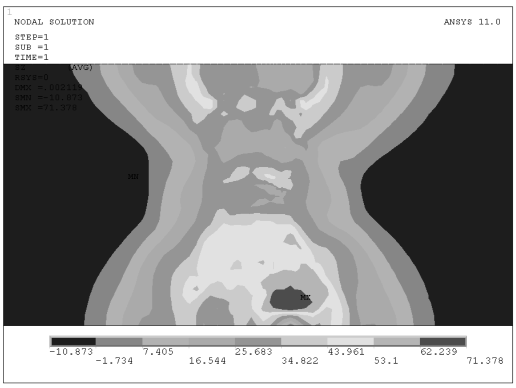
Fig. 5 shows the welding residual stress profiles on the FCAW welded joints. The magnitude of each welding residual stress was in a similar order to that observed with the EGW welded joints. When the former deposited weld was inputted by heat of later welding, the welding residual stress in the former weld region decreased. In contrast, the residual stress in the later welding part was increased by the restraint of the former deposited weld. The maximum residual stress on the specimen surface was caused by a rapid temperature change due to heat transfer from the surface. A comparison of the welding residual stress by the welding process confirmed that the stress was due to the higher heat input in EGW.



(a) σ_{xx}



(b) σ_{yy}



(c) σ_{zz}

Fig. 5 Welding residual stress profiles on the FCAW welded joints

Moreover, the tensile residual stresses to each direction appeared to be higher in the EGW welded joints and were distributed more widely than that of the FCAW, and these trends were similar by way of the crack tips. Fig. 5 shows the welding residual stress on the crack tip of the FCAW welded joints. The welding residual stress examined in the width direction σ_{xx}. A compressive component was produced on the crack tip, which means that this compressive stress can help prevent or decrease the crack opening by closing the crack face, even if an external force is not loaded.A comparison of the characteristics of the distributed welding residual stress through the crack tip by the welding process showed that the residual stress in the width direction, σ_{xx}, in EGW welded joints, which is closely related to the crack opening -closure behavior, was tensile residual stress on the notch tip, whereas that of FCAW was compressive residual stress.

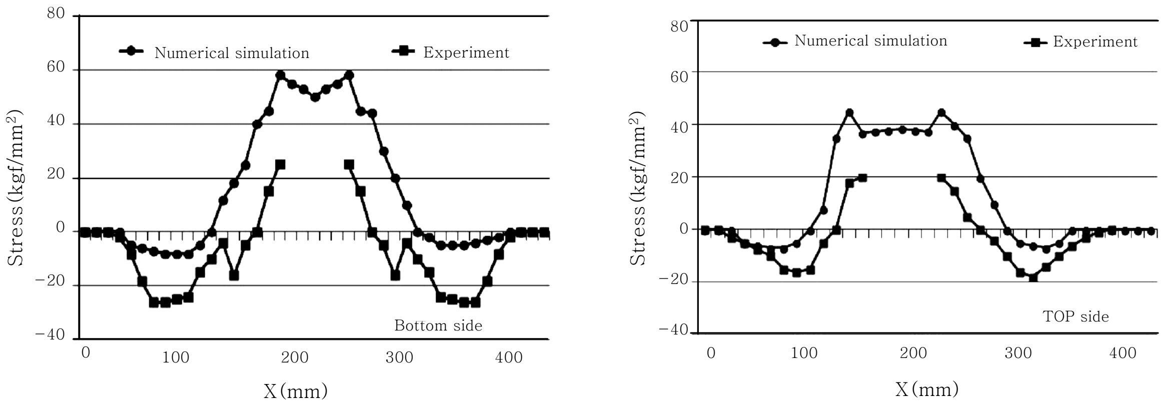
Fig. 6 shows the calculated values and experimentally measured values along the width direction at about 1 mm below the top surface and bottom of the weld specimen. The distributional aspects and the amount of stresses were consistent but the numerical results were slightly higher than the measured values. Conclusively, in qualitative aspect, the residual stress distribution showed similar characteristics.

3.2 Comparison of residual stress relaxation by notch effect in EGW and FCAW welded joints

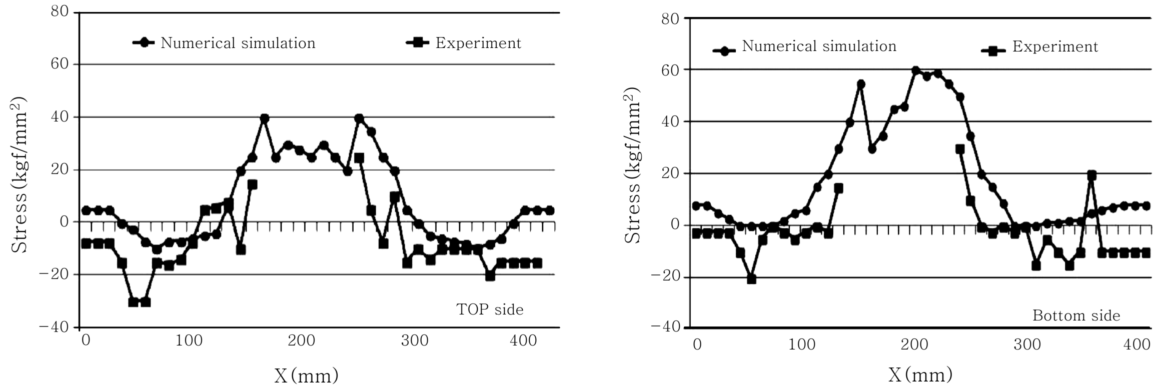
Similar to the 3-point bend test, a notch and initial crack was provided on the CGHAZ, on which the lowest toughness was observed, and the characteristics of the stress distribution around the notch and crack tip were examined when an external load was applied.

Welding residual stress distribution of the EGW and FCAW welded joints before notch preparation has been observed in Fig. 4 and 5 of previous section 3.1. This section intended to clarify welding residual stress distribution of the welded joints after notch preparation.

Fig. 7 shows the residual stress distribution of the



(a) EGW welded joint



(b) FCAW welded joints

Fig. 6 Comparison of the welding residual stress values for EGW and FCAW welded specimen: (Left) top side, (Right) bottom side

EGW and FCAW welded joints after notch preparation. The distributions of the welding residual stress EGW welded joints were a tensile stress around the notch tip before providing a notch, but the distribution of all residual stress components around the notch tip changed to a compressive residual stress after providing a notch, and this trend decreased gradually with increasing distance from the notch tip. In particular, σ_{xx}, which is closely related to crack opening-closure, changed to compressive stress after providing a notch, whereas the tensile stress promoted a crack before providing a notch. As shown on these contours of the FCAW welded joints, σ_{xx} and σ_{yy} increased and changed to compressive stress, respectively, while the tensile σ_{zz} decreased.

In addition, compressive σxx, which is closely related to the retardation of crack opening, increased sharply after providing a notch.

3.3 Comparison of plain strain fracture toughness KIC in the EGW and FCAW welded joints

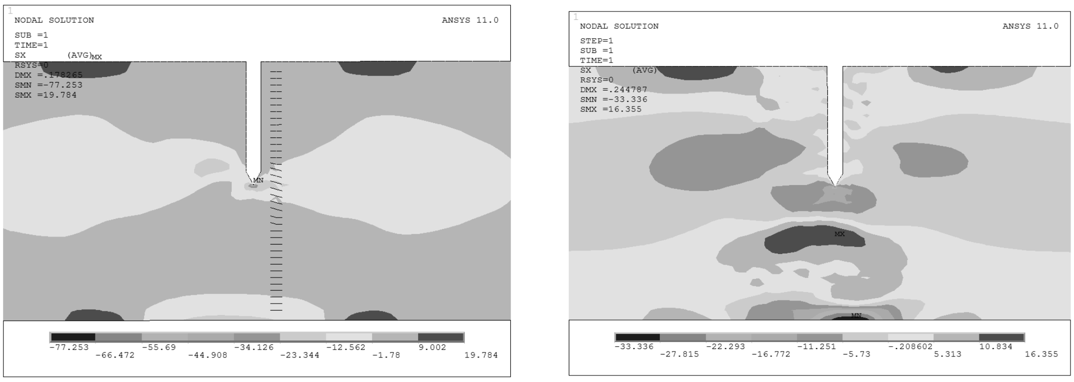
Fig. 8 shows the fracture criteria for the crack-induced welding region by the welding process.

In contrast to the EGW, the fracture toughness of the FCAW increased at the superposition when the crack length was small, but this effect of the residual stress disappeared with increasing crack length. A welding structure is safe when the fracture toughness of that structure has a low value. The EGW is more vulnerable to crack propagation than FCAW because of the lower fracture toughness value than FCAW but as this difference was not large.

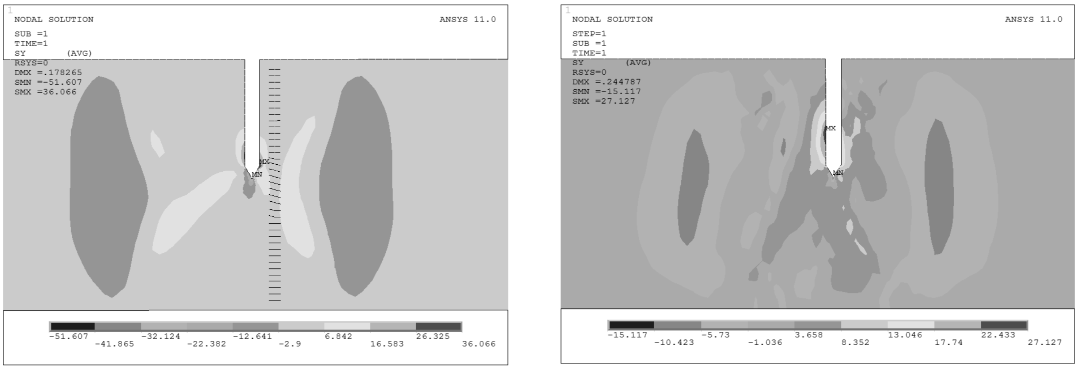
4. Conclusions

1) Owing to the higher heat input in EGW, the tensile residual stresses to each direction were higher in the EGW welded joints and were distributed more widely than that of the FCAW, and these trends were similar through the crack tips.

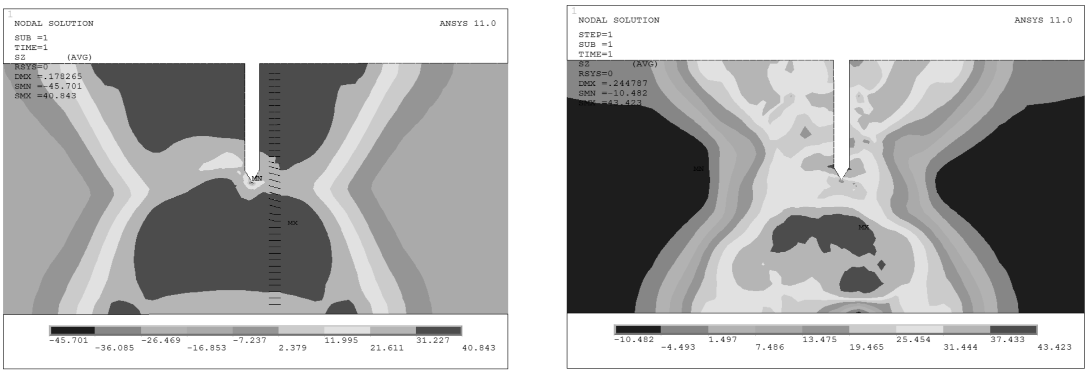
The welding residual stresses(σ_{xx}) in EGW, which are closely related to the crack opening-closure behavior, showed tensile residual stress on the notch tip, whereas that of the FCAW showed compressive residual stress. The distribution of residual stress through the crack tip



(a) σ_{xx}

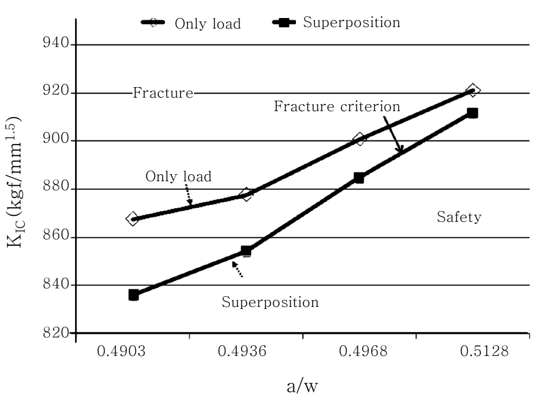


(b) σ_{yy}

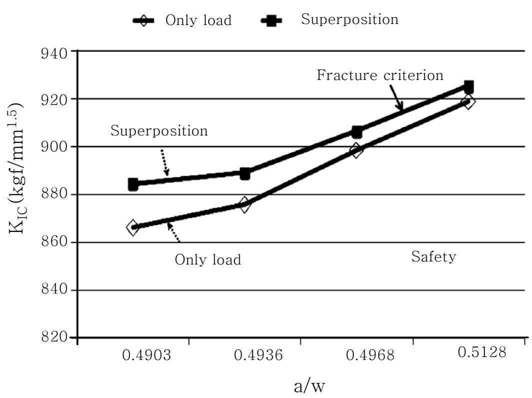


(c) σ_{zz}

Fig. 7 Welding residual stress distribution of the EGW and FCAW welded joints after notch preparation: (Left) EGW, (Right) FCAW



(a) EGW welded joints



(b) FCAW welded joints

Fig. 8 Comparison of the K_{IC} for welded specimens with various initial crack length to width ratios means that a crack can be closed without an external force in FCAW, whereas the notch tip in EGW can be opened with that external load.

2) As the distributions of welding residual stress were changed when a notch was machined on the specimens, the contours of the residual stress(σ_{xx}) via the notch tip were changed to tensile from the compressive residual stress in the EGW, whereas the contour of the compressive residual stress(σ_{xx}) became larger than the existing compressive residual stress.

Although the level of compressive residual stress(σ_{xx}) at the notch tip of the FCAW was lower than that of the EGW, the compressive residual stress in the FCAW was distributed more widely than that of the EGW.

3) A comparison of the fracture toughness KIC between the EGW and FCAW welded joints showed that the K_{IC} of the EGW welded joint was lower than that of the FCAW. Therefore, crack propagation can occur easily in the EGW welded joint but this difference was not large.

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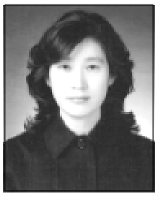

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