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◉ 論　文

Fracture Analysis of Weldments Using the J-integral

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J-integral을 위한 용접부 파괴해석

심 용 래*

Key Words : J-integral(J-적분), Welding(용접), Finite Element Method(유한요소법), Residual Stress(잔류응력), Plastic Strain(소성변형율)

초 록

용접부의 파괴특성을 J-적분을 이용하여 유한요소법으로 해석하였다. 용접부의 열전달 해석 및 응력해석을 수행한후 crack을 도입하여 crack 주위의 잔류응력 해석을 통하여 crack tip에서의 J-적분치를 계산하였다. 이차원 및 삼차원에서의 파괴해석을 위한 modeling 과정을 소개하였으며 대표적인 계산결과를 소개하였다.

1. Introduction

Fusion welding produces a nonlinear thermal loading due to localized heating which results in a nonuniform temperature distribution in weldments. After welding, residual stresses are created in the structure due to plastic strains caused by localized heating of the structure. Two major effects of welding residual stresses are distortion and fracture of welded structures.

Residual stress increases crack driving force and largely affects the strength and resistance to brittle fracture of the structure. Tensile residual stress around the weld area is major factor contributing to cracking and fracture problems in heavy structures with welded thick plates. When there is no data for residual stress distribution, yield stress is often used as a residual stress magnitude for as-welded structures in fracture assessment guidelines. The yield stress value is conservative and sometimes results in unnecessary repair of discontinuities. Therefore it is necessary to accurately assess the magnitude and distribution of residual stresses throughout the thickness of the plate.

Linear elastic fracture mechanics can be used for weldment fracture analysis. Stress intensity

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factors for a residual stress field and external loading can be linearly superimposed for combined loading. However, the use of linear elastic fracture mechanics is limited to small scale yielding only. Another approach to fracture assessment of weldments is the concept of crack tip opening displacement. CTOD design curves can be used for determination of acceptable sizes of defects in welded plates, which sometimes result in a very conservative analysis.

With the development of finite element techniques, the J-integral can be very effectively used for fracture analysis of structures. The J-integral was developed by Rice(Ref. 1) as a fracture parameter in elastic-plastic fracture mechanics. Many investigators suggested other energy integral expressions to expand the J-integral to include incremental plasticity or the effect of thermal loading. Wilson and Yu(Ref. 2) developed a modified expression of the J-integral for combined thermal and external loading in an elastic body. Blackburn et al.(Ref. 3) and Aoki et al.(Refs. 4 and 5) have proposed new path-independent integrals, J^* and $\hat{J}$, respectively, for elastic-plastic problems. Shin (Ref. 6) developed a domain integral expression of the J-integral for a three dimensional crack front under thermal stresses.

Another approach to elastic-plastic fracture mechanics was developed by the General Electric Company. They developed an engineering procedure for the calculation of the J-integral for strain hardening materials(Ref. 7), which was further developed for combined secondary stress and external loading(Ref. 8). Another approximation procedure was developed by Chell(Ref. 9) to incorporate secondary stresses in the J-integral evaluation.

The objective of this research is to develop a guideline procedure for two dimensional or three dimensional finite element modeling of the J-integral analysis for combined residual stress and external loading for a welded plate.

2. Finite element modeling

Finite element models were developed for thermal and residual stress analysis. They were used to evaluate temperature and thermal stress history of a welded plate. The heat transfer and stress analysis of weldments are nonlinear, time dependent, and require large amounts of computer time. Though computer technologies are greatly advanced, reducing the computational time required, it remains a major user task to reduce the computational time for finite element analysis of welding problems.

An uncoupled thermo-mechanical analysis was performed. The thermal analysis was performed and the temperature history was stored, for later use as a thermal loading input in the subsequent stress analysis.

The finite element method can be efficiently used to evaluate the J-integral with a good accuracy. The virtual crack extension method(Refs. 10 −12) is generally used in finite element calculation, where the decrease in potential energy is calculated with respect to virtual crack advance. The J-integral loses its path-independency when there is an inelastic strain or a crack surface traction. Shih et al.(Ref. 6) developed an alternative J-integral expression for a thermally stressed body. A commercial finite element package ABAQUES, which was used in this research, incorporated Shih's procedure for the calculation of J-integral values for combined external and thermal loading(Refs. 13−14).

However, the procedure can not be directly applied to welded plates with a residual stress field, where initial stresses and plastic strains create path-dependency of the J-integral values for different contours. To evaluate the J-integral values at the crack tip in combined residual stress and external loading, very small elements are needed around the crack tip. The J value at those small elements around the crack tip was used as the J-integral value for combined residual stress and external loading.

2. 1 Thermal analysis

Time increments used in the analysis were dependent on the magnitude of the temperature gradient. Time increments were small enough to describe the thermal history of the model accurately. The maximum allowable temperature change between time increments was limited to 110℃. The temperature data for each time increment was saved for thermal loading to use in the mechanical analysis. An arc efficiency of 85 percent was used for the net heat input to the plate for the GMAW process. Heat losses or gains from phase transformation were neglected. A free convection boundary condition was assumed for both top and bottom surfaces of the plate.

A ramp heat input function was developed to apply heat flux to the model gradually with variable ramp times. The ramp heat input model was used to avoid numerical convergence problems caused by an instantaneous increase in temperature near the fusion zone.

Eight-node rectangular elements were used for the two dimensional thermal and mechanical analysis. Twenth-node elements were used for three dimensional analysis of a bead on welded plate. Temperature dependent material properties were used.

2. 2 Mechanical analysis

Residual stresses are the final state of internal stress caused by permanent plastic strains accumulated during multiple heating and cooling cycles of a welding process. Therefore, a complete history of the temperature distribution throughout the plate is required for the calculation of residual stresses.

Free boundary conditions were assumed for all the free surfaces except at the center line of the cross section, where symmetry conditions existed. Volume changes due to phase transformations were neglected. Initial stresses and strains were assumed as zero.

The same finite element meshes and time steps were used for both the thermal and residual stress analysis. The temperature history obtained in the thermal analysis was used as a thermal loading in the residual stress analysis. The results of the residual stress analysis was used for the J-integral estimation of combined residual stress and external loading.

2. 3 J-integral analysis

The procedure for J-integral analysis with combined thermal and external loads cannot be directly applied to welded plates with a residual stress field. Initial stresses and plastic strains caused by welding create path-dependency of the J-integral value at different contours. To evaluate the J-integral value at the crack tip for combined residual stress and external loads, very small elements are needed around the crack tip. The J-value at the nearest contour to the crack tip can be used as an approximate solution for the J-integral with combined residual stress and external loads. Quarter point singular elements were used to model the singularities at the crack tip with focused mesh around the crack tip.

The J-intergral estimation of a welded plate, subjected to the combined loads of a residual stress field and an external force, was performed in three steps as follows :

1) Thermal analysis : Temperature history of the plate was calculated from heat input to the

model.

2) Residual stress analysis : Residual stress was evaluated using the temperature history obtained from the previous step.

3) The J-integral analysis : A crack was introduced in the residual stress field and an external load was applied to calculate a J-integral value for the combined loads.

An overall procedure for this analysis is shown in Figure 1.

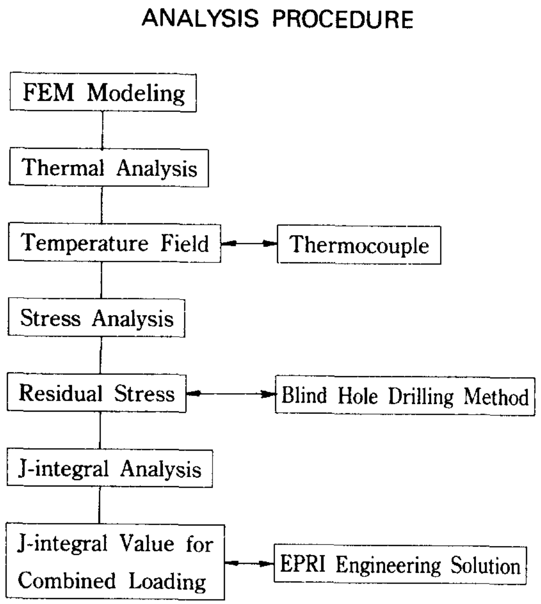


Fig. 1 Analysis procedure of the J-integral for combined residual stress and external loads

3. Results and discussion

3. 1 Welded thin plate with a center crack

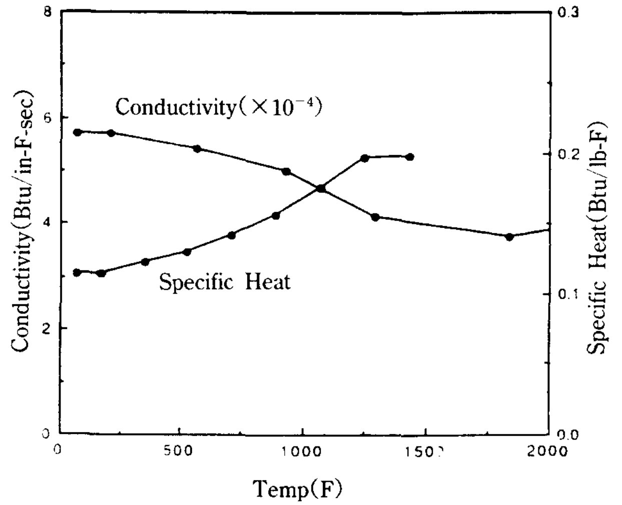


Fig. 2 Temperature dependent thermal properties of A515 steel

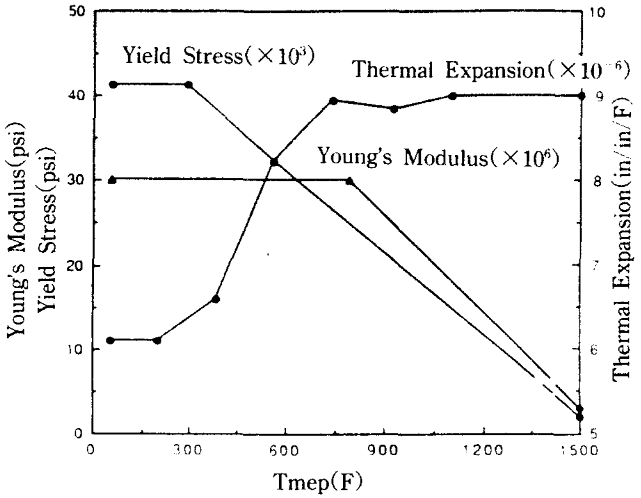


Fig. 3 Temperature dependent mechanical properties of A515 steel

A J-integral analysis was conducted for a center cracked plate of A515 grade 70 steel subjected to combined residual stress and external loads. Temperature dependent thermal and mechanical properties were used shown in Figure 2 and Figure 3. The Ramberg-Osgood stress-strain relationship was used for the analysis, which was selected to closely represent the stress-strain curve of A515 steel(see Figure 4). Figure 5 shows the geometry of the specimen with a center crack. A line heat source was used to generate the welding thermal load at the centerline of the plate. Welding current, voltage, and speed were assu-

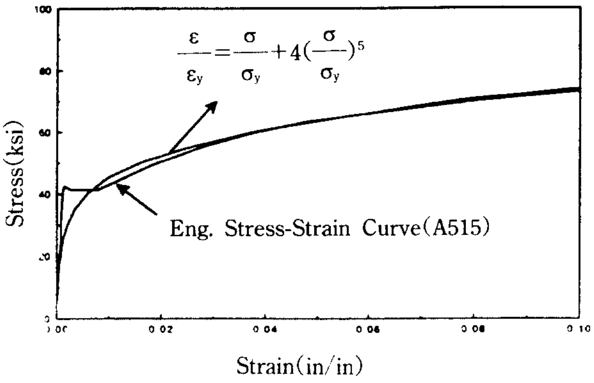


Fig. 4 Engineering stress-strain curve and Ramberg-Osgood relationship of A515 steel

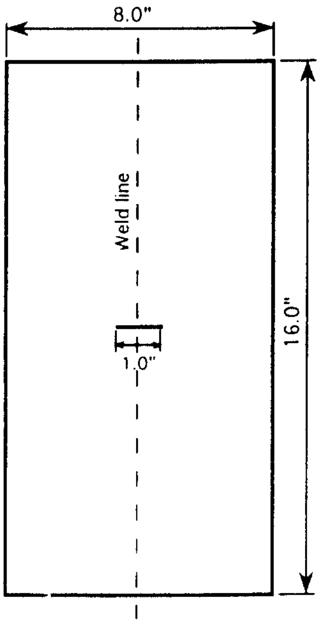


Fig. 5 Specimen geometry of a welded thin plate with a center crack

med as 200A, 25V, and 5.1mm/sec, respectively. The arc efficiency was 0.85 for the GMAW process. Due to symmetry, one quarter of the plate was modeled. The finite element mesh contained ninety eight elements as shown in Figure 6. The plane stress assumption was used for residual stress and the J-integral analysis.

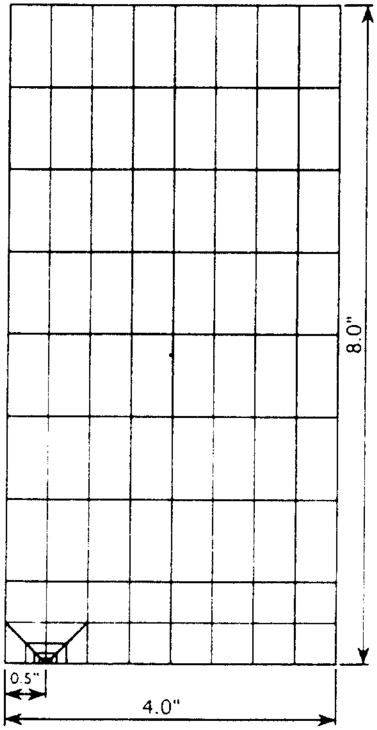


Fig. 6 Finite element mesh for a quarter of a welded thin plate with a center crack

Temperature histories and residual stress distributions were obtained from thermal loads along the centerline of the plate. Figure 7 shows the redistribution of longitudinal(welding direction) residual stresses at the centerline of the plate (crack plane) due to crack initiation and growth. The maximum tensile stress of 316 Mpa, without a crack, increased slightly around the crack tip, at the crack initiation stage. This tensile stress gradually decreased as the crack propagated, from the effects of compressive residual stresses outside the weld area.

Figure 8 shows somparisons of J-integral values computed using FEM, EPRI solution and Chell's approximation solution. Because the J-integral loses its path-independency in the residual stress field, the J value at the nearest contour to the crack tip was used as a finite element solution. The engineering solution from the EPRI procedure was also calculated and plotted for comparison. The two results show good agreement.

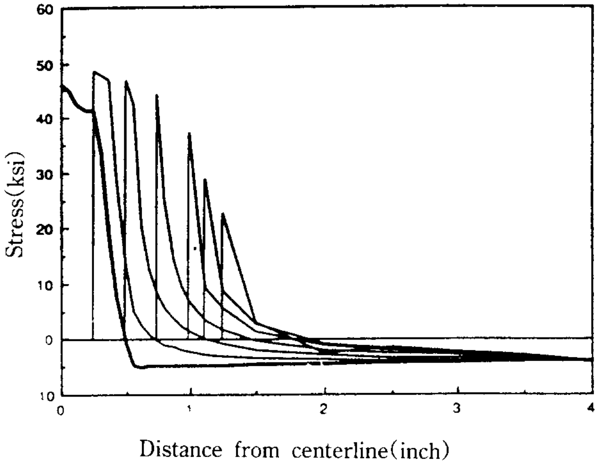


Fig. 7 Redistribution of longitudinal(welding direction) residual stresses due to a crack propagation

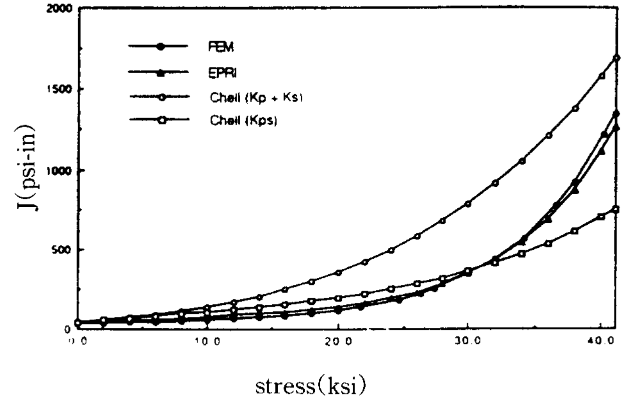


Fig. 8 Comparison of the J-integral vs. external loading for a welded thin plate by finite element method, EPRI solution, and Chell's sloution

Chell's approximation solution(Ref. 9) was calculated and compared with FEM and EPRI solution. For the calculation of the J-intergral, following assumptions were used :

$$\frac{\varepsilon}{\varepsilon_y}=\frac{\varepsilon}{\varepsilon_y}+4\left(\frac{\varepsilon}{\varepsilon_y}\right)^5 \quad \text{(Ramberg-Osgood relation)}$$

$$F(L_r^*)=\alpha(\sigma_{ref}/\sigma_y)^{n-1}$$

where, $\alpha=4.0$ and $n=5$

$m(a, t)=2[1-(a/t)]/3$
$L_r^*=1.25$
$\sigma_y=283\text{Mpa}$

Bacause the sum of stresses from external loads and the peak value of residual stress exceed the yield stress of the material, redistributed stresses for an uncracked plate were calculated using the finite element method. Those redistributed stresses were used to calculate the displacement field with an elastic stress-strain relationship. Subsequently, stress intensity factors for combined primary and secondary loads(K^{ps}) were calculated by the displacement method. Elastic solutions of the J-integral were calculated from those stress intensity factors. Additionally, J-integral values calculated from linearly superimposed primary and secondary stress intensity factors(K^p+K^s) were also plotted, which overestimated the J-integral based on $K^{ps}(K^p+K^s > K^{ps})$. Chell's solution showed lower J-integral values at large external loads above 207 Mpa when compared to the FEM or EPRI solutions.

3. 2 Three dimensional analysis of a bead on plate weld

A J-integral analysis was conducted for a three dimensional model of a bead on plate weld with a single edge notch. The geometry and dimensions of the specimen are shown in Figure 9. The

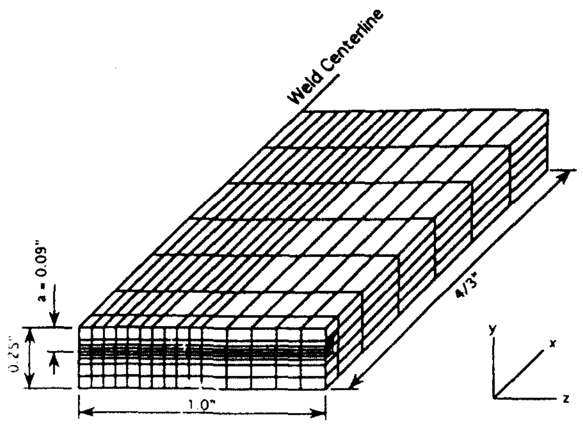


Fig. 9 Three dimensional finite element mesh for a bead on plate

thickness of the plate is 6.4mm with a 2.3mm deep single edge crack throughout the width of the plate. Due to symmetry, half of the plate was used for a finite element mesh as shown in the figure. Seven hundred thirty five(735) twenty-node three dimensional elements were used for both thermal and mechanical analysis. Quarter point singular elements were used, with a focused mesh around the crack tip. Material properties for A515 grade 70 were used in the analysis. The engineering stress-strain curve of A515 was used for the analysis(Ref. 15), shown in Figure 4.

The gas tungsten arc process was used for deposition of the bead on the plate. Welding current, voltage, and speed were assumed as 200A, 10V, and 2.2mm/sec, respectively. An arc efficiency of 0.35 was selected for the GTAW process. A heat flux was applied to the centerline elements of the top surface at the same time.

Uncoupled thermal-mechanical analysis was used. Thermal analysis was performed first, and then the residual stress was analyzed using the temperature history from the thermal analysis. Free boundary conditions were assumed for the analysis, except at the centerline of the plate, where a symmetry condition was applied. Figure 10 shows the through thickness distribution of longitudinal(welding direction) stress at different distances from the weldline. The maximum tensile stress was 554 Mpa at the centerline and gradually decreased along the transverse direction. The size of the tensile stress zone was 10.2 mm, as shown in the figure.

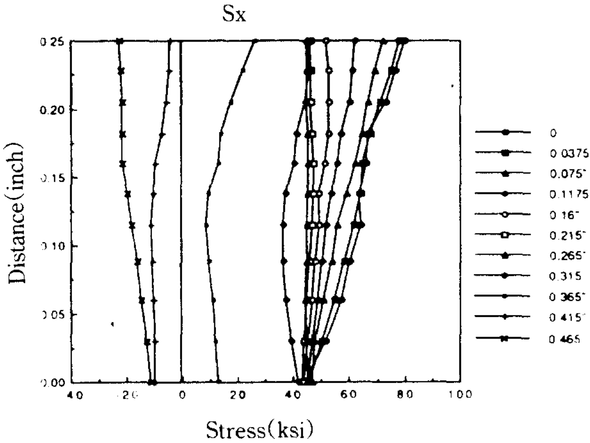
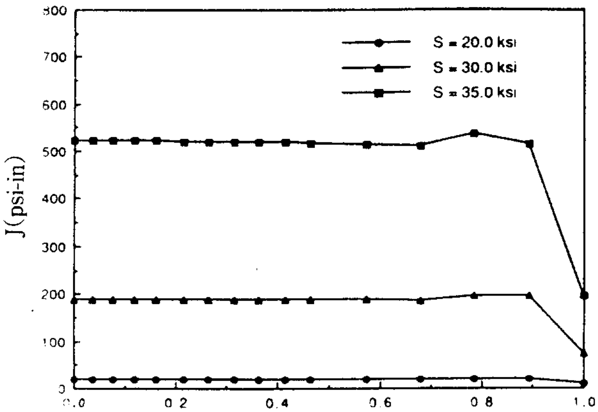


Fig. 10 Through thickness distribution of transverse(perpendicular to welding direction) residual stresses for a bead on plate at different distance from the weldline

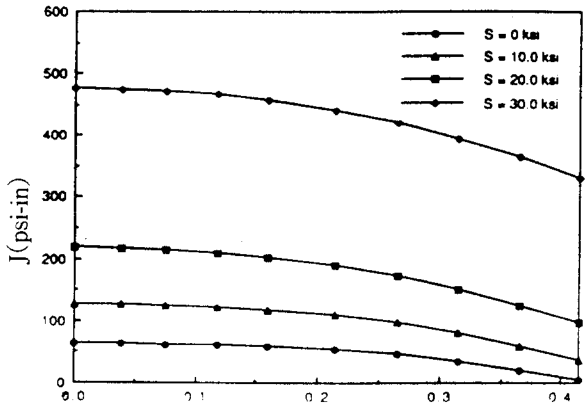
The J-integral value was evaluated as a function of the crack tip location. The change of J-integral values along the Z-direction for external loads of 138, 207, and 241 Mpa(without residual stress) were shown in Figure 11. The J-integral showed almost the same value along the length, but sharply decreased at the end of the plate due to the effect of the free surface.

A J-integral analysis was also performed for combined residual stress and external loads. A crack was introduced to the residual stress field by changing the boundary conditions, and then external loads were applied to calculate the J-integral for the combined loads. The J value at the nearest contour to the crack tip was assumed as a finite element solution for the J-integral. The



Distance(inch)

Fig. 11 The change of the J-integral value along crack location of a bead on plate for different loads(external loads only)(S : external load)

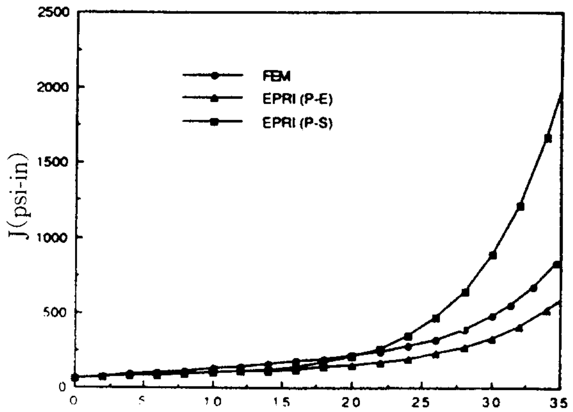


Distance(inch)

Fig. 12 The change of the J-integral value along crack location of a bead on plate for different loads(combined residual stress and external loads)(S : external load)

results of these J values are plotted in Figure 12 as a function of the crack tip location along the Z-direction(perpendicular to the weldline) for various external loads up to 207 Mpa. The J-integral had a maximum value at the centerline of the plate and then gradually decreased along the Z-direction, due to the decrease of tensile residual stresses. Without an external load(residual stress only), the J-integral showed a maximum value of 0.011 Mpa-m at the centerline, which was equivalent to an external load of 170 Mpa without residual stress.

EPRI solutions, with a plane strain assumption, were calculated and compared with the numerical results in Figure 13. The Ramberg-Osgood relation used for the EPRI solution was selected to closely represent the engineering stress-strain curve of A515 steel(see Figure 4). EPRI solutions showed a lower value than the finite element solution for the external load above 103 Mpa. The difference between the two solutions gradually increased as the external load increased up to 28 % for an external load of 241 Mpa. The plane stress EPRI solution was plotted for reference purposes and showed higher J-integral values compared with the finite element or plane strain EPRI solution for the external loads above 138 Mpa.



Stress(ksi)

Fig. 13 Comparison of the J-integral for combined residual stress and external loads between finite element analysis and EPRI solution.

4. Conclusions

Finite element models were developed for two dimensional and three dimensional residual stress analysis and the J-integral evaluation for combined residual stress and external loading. The J-integral analysis of a welded plate was carried out in three steps :

1) Thermal analysis : Calculation of temperature history

2) Residual stress analysis : Evaluation of residual stress field from calculated thermal history

3) The J-integral analysis : Estimation of the J-integral value for combined loading including external loading and a residual stress field obtained from the previous step

A ramp heat input function was used in the thermal analysis. Twenty percent of actual heat input time was used as a ramp time, which was determined by the comparison of previous experimental results and finite element solutions(Refs. 16－17).

The J-integral of combined residual stress and external loads was calculated for a welded thin plate with a center crack. The J value at the nearest contour to the crack tip was assumed as a finite element solution for the J-integral. The EPRI solution and Chell's solution were compared with finite element results. The EPRI solution agreed well with finite element solution, but Chell's approximation solution showed lower J values than other solutions for external loads above 207 Mpa.

Three dimensional analysis was carried out for the J-integral analysis of a bead on plate. The J values were determined as a function of the location at the crack front. The EPRI plane strain solution showed lower value than the finite element solution for external loads above 103 Mpa.

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