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EVALUATION OF J-INTEGRAL FOR CRACK IN SINGLE-V BUTT WELD JOINT IN PRESENCE OF RESIDUAL STRESSES

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Abstract - The evaluation of J-integral for crack in the presence of welding residual stresses is computationally complex. In this study J-integral is calculated for crack located in single-V butt joint of austenitic stainless steel plates of grade 316L.To obtain residual stresses from welding, a decoupled thermo-mechanical analysis is performed. An advanced element birth and death technique is used to represent weld deposition process. Mapping stress method is used to transfer the weld induced residual stresses to a stress free component in which a crack is introduced at the center of weld. The effect of combined loading of weld induced residual stresses and an external mechanical load on distribution J-integral value are studied. The results of welding simulation are in good agreement with literature. The values of J-integral obtained as a result of crack body analysis shows good path independence. The J-integral values exhibit variation across thickness direction from root towards the mouth of weld joint.

Keywords - Welding Simulation, Element Birth and Death, Residual Stresses, J-Integral.

I. INTRODUCTION

Residual stresses are unavoidable in welded constructions. Correct prediction of residual stresses and assessment of their effect on structural integrity is a fundamental issue. One of the most important aspects of such study is to predict the effect of welding residual stresses on the behavior of crack like defects in weld [1]. The procedural aspects of obtaining welding induced residual stresses for a plate component and to understand the effect of these residual stresses on J-integral calculations for crack embedded in such regions is complex.

The J-integral [2] has been used to characterize the crack opening driving force, crack tip stress field and the strain energy release rate during crack growth, The J-integral as a path independent parameter is defined as

$$J = Lim_{\varepsilon\to 0} \int_{\varepsilon} \left(W\, \partial_{ij} - \sigma_{ij} \frac{\partial u_j}{\partial x} \right) n_i ds$$

where '*W*' is the strain energy density, σ_{ij} and u_j are components of stress and displacement, respectively, in Cartesian coordinates, the '*ds*' is a length increment along an arbitrary contour path 'ι' taken as counter clockwise around the tip of the crack and ∂_{ij} is thekronecker delta tensor. J-integral estimation for a cracked body under combined residual stress and other mechanical load becomes path-dependent due to the initial strains corresponding to the residual stresses [3]. Recently the problem of J-integral evaluation in the presence of welding residual stresses has been investigated by numerical technique by Lei et.al [3-6].

Lei [3, 4] modified J-integral definition for general initial strain problems withnon-proportional loading and developed methods for the evaluation of initial strains in finite element analysis [3]. The J-integral definition given in [4] is referred to as "modified J". The modified J-integral definition is given as,

$$J = \int_{\varepsilon} \left(W\, \partial_{ij} - \sigma_{ij} \frac{\partial u_j}{\partial x} \right) n_i ds + \int_A \left(\sigma_{ij} \frac{\partial \varepsilon_{ij}}{\partial x} - \frac{\partial W}{\partial x} \right) dA \qquad (2)$$

where*A* is the area enclosed by 'ι ' and the strain energy density, *W*, is defined as mechanical strain energy density by Lei [4, 5].

$$W = \frac{1}{2}\sigma_{ij}\varepsilon_{ij}{}^{e} + \int_{\varepsilon_{ij}{}^{p}{}_{ubc}}^{\varepsilon_{ij}{}^{p}} \sigma_{ij} d\varepsilon_{ij}{}^{p} \quad (3)$$

$where\ \varepsilon^{\ e}\ and\ \varepsilon^{\ p}$ are elastic and plastic strains respectively and $\varepsilon^{\ p}{}_{ubc}$ is un-cracked body plastic strains.In commercial finite element software [7], the above definition of J-integralis implemented as below,

$$J = \int_{\varepsilon} \left(W\, \partial_{ij} - \sigma_{ij} \frac{\partial u_j}{\partial x} \right) n_i ds + \int_A \sigma_{ij} \frac{\partial \varepsilon_{ij}{}^{th}}{\partial x} dA + \int_A \sigma_{ij} \frac{\partial \varepsilon_{ij}{}^{0}}{\partial x} dA \qquad (4)$$

The strain energy density$W$ definition from eq. (3) has been used except that $\varepsilon_{ij}{}^{p}{}_{ubc} = 0$.

where $\varepsilon_{ij}{}^{th}$ and $\varepsilon_{ij}{}^{0}$ represents thermal strains and initial strains respectively. The J-integral definition from Eq.(4) includes the effect of thermal strains and initial strains and can handle welding residual stresses which are included as initial condition.

The published work for the subject has been found to be mostly related to cracks in single pass weld region. The present study adopts such published procedure for J-integral calculation for cracks in multi-pass single V-joint.

Initial part of the paper explains the procedure followed for J-integral calculation in presence of welding residual stresses. Subsequently validation of this procedure is presented in terms of comparison of results obtained for a typical case [6]. This is followed by application of the procedure for J-integral calculations for a crack in multi-pass single V-joint.

II. PROCEDURE FOR J-INTEGRAL CALCULATION

Fig.1 shows the flow chart of the procedure used to obtain J-integral values for a crack in the vicinity of residual stresses arising from welding process.

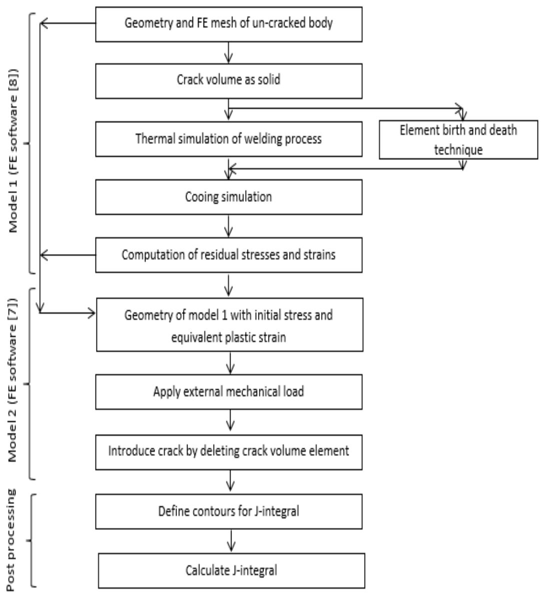

Fig. 1 procedure for J-integral evaluation in presence of welding residual stresses

The first step in the procedure is creating geometry and finite element mesh of welded plate. The crack volume initially is created in the modeling step which will be deleted in the later stage. The second step is simulation of welding process by using element birth and death technique [8]. The welding is simulated by performing a decoupled thermo-mechanical analysis for computation of residual stresses. To perform the fracture analysis for estimation of J-integral finite element software[7] is used since the J-integral definition implemented in the [8] does not consider the effect of residual stresses. The geometry of model along with residual stresses and equivalent plastic strain is imported in [7]. The next step is to create a crack by deleting the crack volume elements. A remote tensile load is applied normal to crack plane. The final step is to perform the contour integration for estimation of J-integral.

III. VALIDATION OF PROCEDURE FOR J-INTEGRAL CALCULATION

The procedure described in section 2 has been validated by applying it to a case investigated by Lei [6].A thin plate of width 2*w*, thickness *B*and length 2*L*with a single-pass slit-weld of length 2*l*and width 2*d*located in the middle of the plate was considered (Fig.2). After welding, acenter crack of length 2*a (a = l)* was then introduced into themiddle of the weld and remote tension perpendicular to the crack plane of σ_{rem} = 0, 9.52, 19.04 Mpawas applied at the ends of the plate. The crack toplate width ratio *a/w*=0.2. The dimensions of the specimen are as follows *w* = *L* = 250 mm, *l* = *a* = 50mm, *d* = 2.5 mm and *B* = 5 mm. The investigation [6] is carried out considering the same material properties used in the present study.

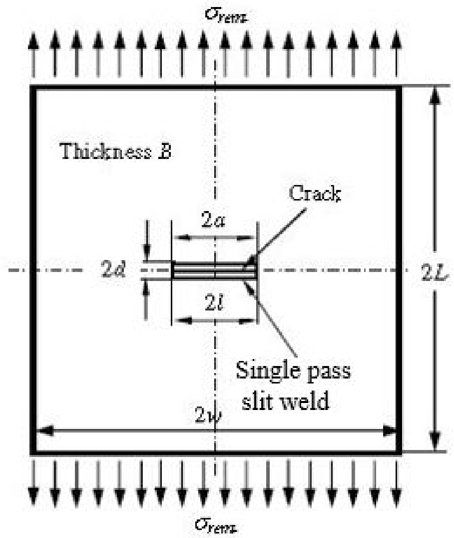

Fig.2 Geometry of a plate with crack in the slit-weld [6].

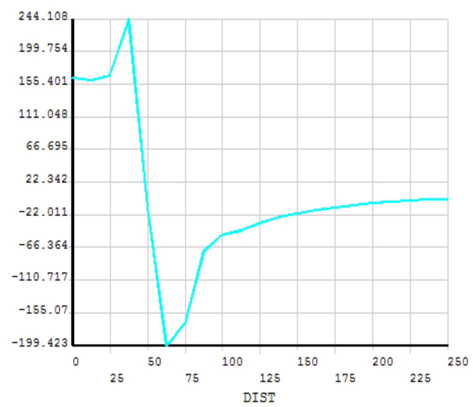

Fig.3Plot of residual stress distribution as distance from center of weld (present study)

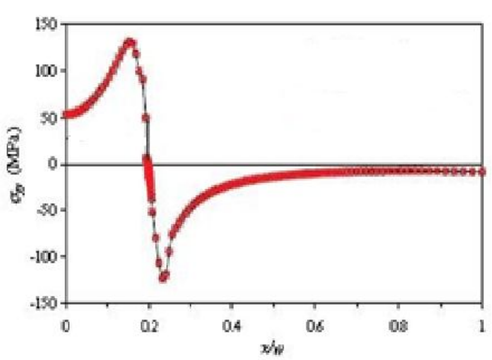

Fig. 4 Plot of residual stress distribution as distance from center of weld [6]

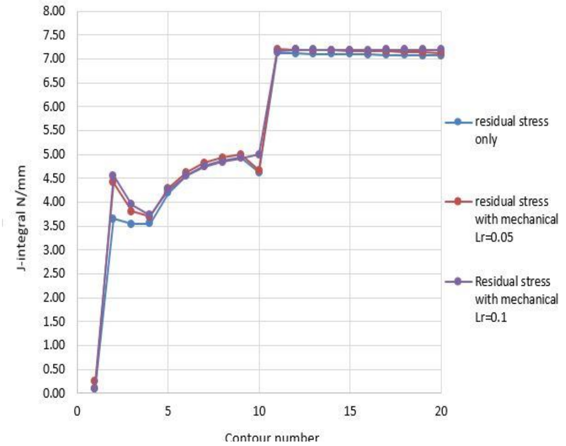

Fig.5J-integral values for different loading conditions (present study).

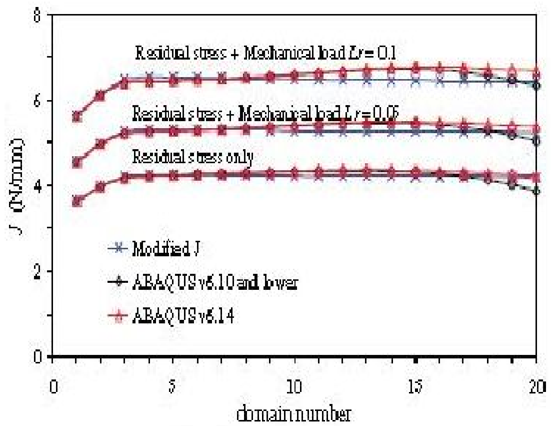

Fig.6 J-integral values for different loading conditions [6].

Fig.3 and 4 shows the results for residual stresses using the procedure of section 2 and those obtained byLei [6] respectively. Fig. 5 and 6 give comparison of J-integral values around crack tip. Both results indicate similar trend and order of magnitude of stress distribution and J-integral values which validate the procedure.

IV. MULTIPASSSINGLE V-JOINT COMPONENT ANALYSIS

Fig. 7 shows the geometry of single V-joint butt weld for joining two rectangular plates. The weld has athrough thickness crack at the center of weld bead. The dimensions of the plate are 50mm wide×100mm long×17.47mm thick. Material of construction is austenitic stainless steel of 316L grade. The V-joint weld bead is fashioned with root gap of 3mm. A crack is modeled at the center of weld zone parallel to the direction of weld bead. To simplify the analysis, the weld material properties are assumed to be same as that for the plate material. Only half symmetric region of plate body is analyzed to reduce computational time. Table1 shows material properties used for the analysis.

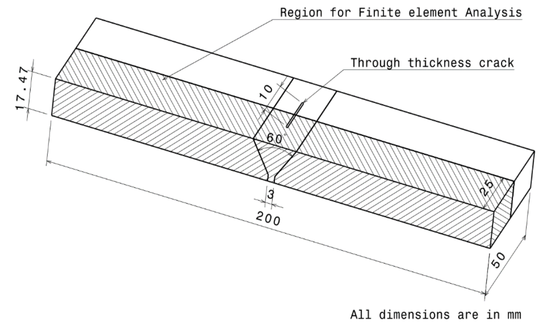

Fig. 7 Geometry of single v-joint plate with crack at center of weld bead.

Temp. (K)	Specific enthalpy (J/m^3)	Young's modulus (N/m^2)	Poisson's ratio	Conductivity (W/mK)	Coefficient of thermal expansion (mm/mmK)
294.26	7.89E-34	1.95E+11	0.3	14.196	1.53E-05
533.15	1.08E+09	1.78E+11	0.3	17.633	1.75E-05
644.26	1.60E+09	1.71E+11	0.3	19.352	1.80E-05
866.48	2.69E+09	1.52E+11	0.3	22.49	1.89E-05
1088.7	3.81E+09	1.25E+11	0.3	25.404	1.94E-05
1644.2	6.88E+09	6.89E+08	0.3	32.876	2.07E-05
1644.3	8.97E+09	689.48	0.3	65.752	2.07E-05

Table. 1 Temperature dependent properties of the material

Fig. 8 shows the true stress-strain curves used for the analysis at different temperatures ranging from ambient temperature to melting temperature of the material.

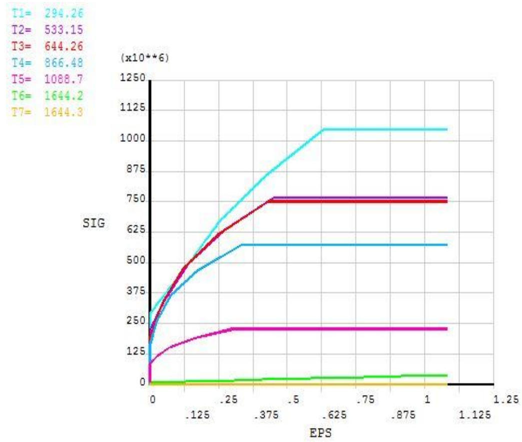

Fig.8 Temperature dependent true Stress- strain curves for SS316L material.

Fig.9shows the discretized model of the welded plate. The plate is idealized by 20-noded 3-D elements. In discretization, element type SOLID 90 is used for thermal analysis and SOLID 186 element type is used for mechanical analyses. Fig.10shows the weld bead with crack located at the center. The crack length is taken as a=10mm. width of the crack is 0.1mm. The ratio of crack length to the plate width is 0.2.

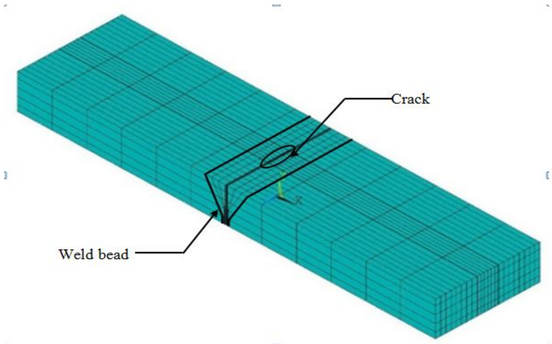

Fig.9 The discretized model of plate.

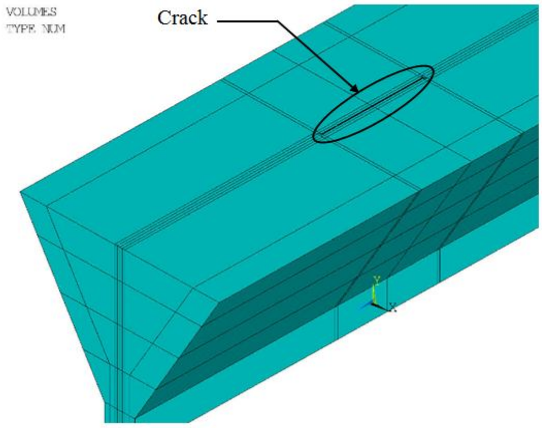

Fig.10 Weld zone volume plot with center crack

4.1 Welding simulation

4.1.1Thermal analysis and Boundary Condition

The first step in welding simulation is to perform a thermal analysis to obtain temperature distribution. A transient thermal analysis is performed matching with the heat input during the welding process and the bead size. To consider the heat transfer by convection and radiation a thermal boundary condition is applied with combined convective and radiation heat transfer coefficient asshown in Fig.11.The ambient temperature is considered as 25°C.Welding speed is considered as 7mm/sec. At the end of all weld bead depositions the model is subjected to cooling for 50 minutes.Fig.12shows the contour plot for nodal solution of temperature distribution obtained as a result of thermal analysis at the end of last pass.

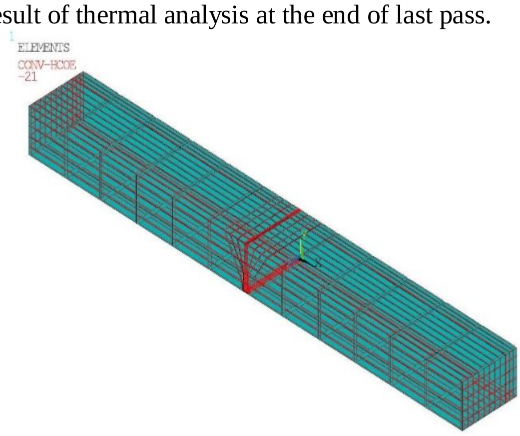

Fig.11 Thermal boundary condition applied to plate

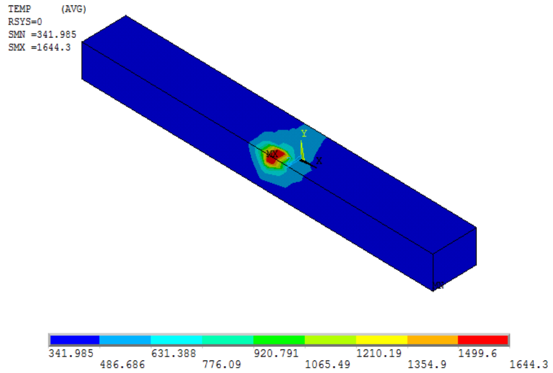

Fig. 12 Contour plot for nodal solution of temperature distribution at the end of last pass.

4.2.2 Structural Loading and Boundary Condition

The second step in welding simulation is to perform a non-linear structural analysis. The nodal solution of temperature distribution obtained from the thermal analysis are read as thermal loading at each load step in the structural analysis. It is performed to obtain stress, strain and displacement fields under thermal load due to the welding. The plate is constrained as shown in fig.13.

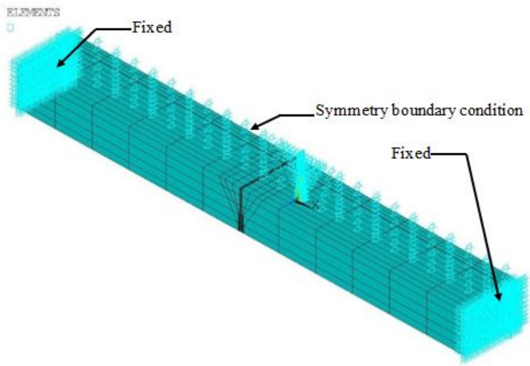

Fig.13 Structural boundary conditions for plate.

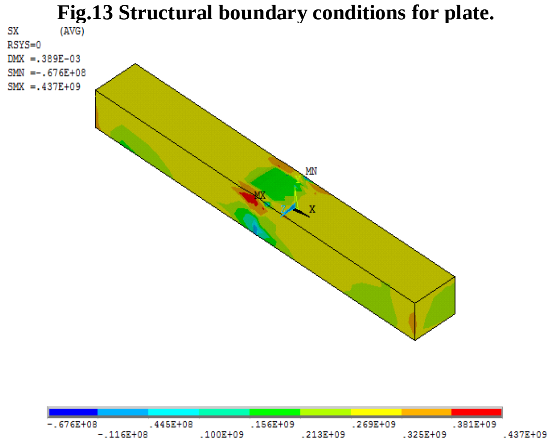

Fig. 14 σ_{xx} stress contour plot for nodal solution of stresses along plate length.

Fig. 14 shows plot of the residualstresses σ_{xx} obtained along the length direction at the end of cooling period. Fig.15 (a) and Fig.15 (b) show the nature of residual stress distribution along the plate length at mid-section, at the top of plate and at the bottom of the plate at middle of crack length and at crack-tip respectively. The peak tensile stresses are observed at the center of weld zone.

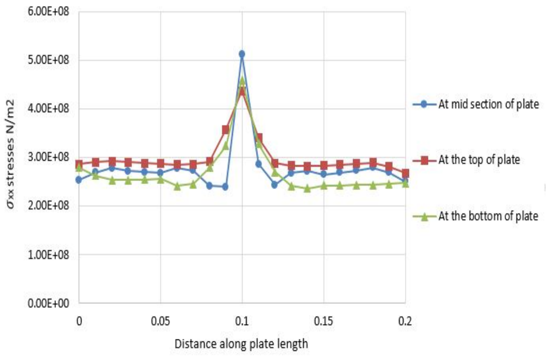

Fig. 15 (a)Residual stresses distribution throughout plate length at middle of crack.

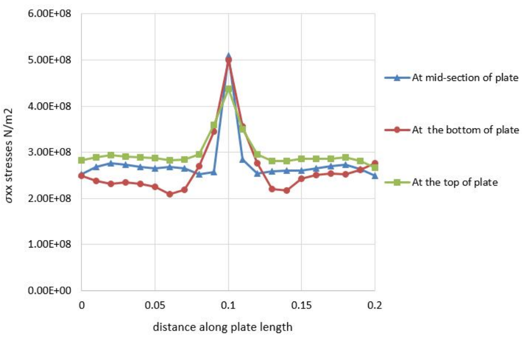

Fig. 15 (b) Residual stresses distribution throughout plate length at tip of crack.

4.3.3 Fracture analysis in presence of residual stresses.

A separate cracked body analysis is performed to obtain J-integral values. J-integral evaluation on a component following the welding simulation is done using a “mapping stress” method[6]. The J-integralis calculated with the help of [7]using its in-built J-integral function.20-noded 3-D elementC3D20R is used for cracked body analysis.In the crack body analysis, the stress fields and the equivalent plastic strain are imported into a new stress-free model as initial condition(for inheriting the strain hardening state after the welding). A crack is introduced at the center of weld by deleting corresponding elements. Remote tensile stressof 76.16 N/mm^{2}is applied in the direction perpendicular to crack plane. This remote stress is calculated according to “R6: Assessment of the Integrity of Structures Containing Defects” [9] as follows. The mechanical load level is measured by L_r, the ratio of applied load per unit thickness, P, to the limit load per unit thickness,P_l as per following relationship

$$L_r = \frac{P}{P_l} = \frac{\sigma_{rem}}{(1-\frac{a}{W})\sigma_0} \qquad (6)$$

whereσ_0 is taken as the 0.2% plastic strain proof stress,$\sigma_0 = 238$ N/mm^{2}and σ_{rem} is the applied remote stress.Mechanical load level is taken as 0.4 and σ_{rem} is calculated as,

$$0.4 = \frac{P}{P_l} = \frac{\sigma_{rem}}{(1-0.2)\times 238}$$

thus, $\sigma_{rem} = 76.16$ N/mm^2

Fig.16 shows the details of the crack geometry located at the center of weld bead. The crack front is defined by the set of nodes on crack face. The normal to crack plane which is a requisite to perform contour integration to obtain the J-integral is in x-direction as shown in Fig.16.

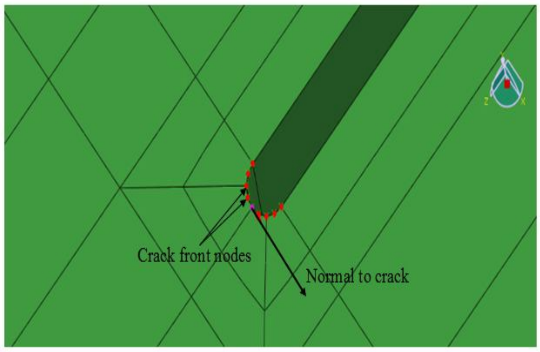

Fig.16Crack interaction specifics of plate.

Fig. 17 shows three crack faces from the top to bottom of the plate where J-integral values are computed.

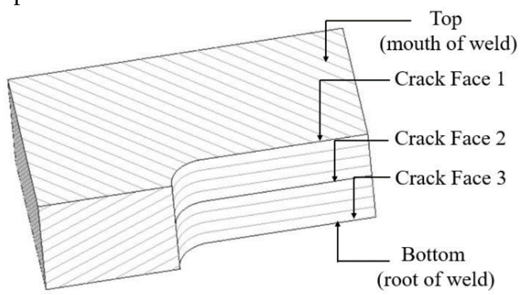

Fig. 17 Crack faces for J-integral calculations

Fig.18 shows the J-integral values under the effect of combined loading of welding-induced residual stresses andremote tensile load. The J-integral values shows good path independence little away from crack tip (after contour no.3).

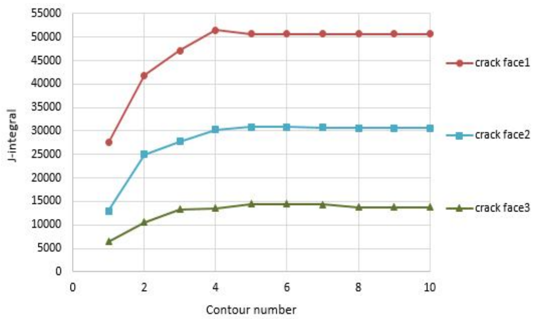

Fig. 18J-integral for combined loading of residual stresses and remote tensile load.

The J-integral values are observed to be the lowest at bottom surface and increase towards top surface of plate. This variation is attributed to the nature of residual stresses (Fig. 15(a), (b)) which too vary in similar fashion from bottom to top surface.

CONCLUSIONS

1. The Prediction of welding residual stresses by performing welding simulation using element birth and death technique with the help of finite element software [8] was successfully implemented for multi-pass single-V weld joint.
2. The J-integral values estimated for a crack in awelding residual stress field using finite element software [7] showgood path independence.
3. The J-integral values as well as residual stresses are observed to increase gradually from root of the single-V weld joint towards the mouth of weld.

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