

Finite Element Analyses of Stress Intensity Factor Solutions for Discontinuous Gas Metal Arc Welds under Lap-Shear Loading Conditions

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ABSTRACT

The distributions of the mode I and mode II stress intensity factor solutions along the fronts of the pre-existing cracks of continuous and discontinuous gas metal arc welds in lap-shear specimens are investigated by three-dimensional finite element analyses. Two-dimensional plane strain finite element analyses were first carried out in order to obtain the computational stress intensity factor solutions for the idealized and realistic weld geometries as the references. Further, the stress intensity factor solutions for realistic welds obtained from the two-dimensional finite element analyses are presented for unequal sheet thicknesses for future engineering applications. Then the stress intensity factor solutions for continuous and discontinuous welds were obtained by three-dimensional finite element analyses. The computational results indicate that the distributions of the mode I and mode II stress intensity factor solutions for the discontinuous welds are quite different from those for the continuous welds. For continuous welds, both the mode I and II stress intensity factor solutions are higher in the middle of the crack front and lower toward the free surfaces. For discontinuous welds, both the mode I and II stress intensity factor solutions become higher near the weld ends or discontinuities with consideration of contact.

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INTRODUCTION

Recently, many investigations on quasi-static and fatigue strengths of gas metal arc welded joints have been conducted. Investigators have reported failure locations near weld roots and near weld toes under quasi-static and cyclic loading conditions [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. In most investigations, the end effects of the discontinuous welds were excluded and the failures at the mid-sections of the welds were studied. Bonnen et al. [10] included the weld ends in some single lap-shear specimens in order to understand the effects of the weld ends on the cyclic loading performance. Under cyclic loading conditions, the failure mode of the single lap-shear specimens with the weld ends excluded was mainly near the weld toe under low load levels and mainly near the weld root under higher load levels. However, the failure mode of the single lap-shear discontinuous weld specimens with the weld ends included was mainly due to fatigue crack propagation from the pre-existing crack at the interfacial plane of the two sheets near the root of the weld through the weld throat.

Weld geometry is one of the key factors affecting the cyclic loading performance of gas metal arc weld joints [7]. Niu and Glinka [12] investigated the effect of weld geometry on the stress intensity factor solutions for welded T-butt joints under a variety of loading conditions. Nguyen and Wahab [13] examined the effect of weld geometry and residual stresses on the fatigue life of butt welded joints based on the stress intensity factor solutions. Feng et al. [11] developed a fatigue life prediction model with the consideration of the crack initiation life at the weld toe, which was estimated using the notch strain approach, and the crack propagation life at the weld toe

based on the stress intensity factor solution for cracks. Cerit et al. [14] investigated the effects of the weld geometry on the stress intensity factor solutions in cylindrical fillet-welded joints.

In this paper, the distributions of the mode I and mode II stress intensity factor solutions along the fronts of the pre-existing cracks of continuous and discontinuous gas metal arc welds in lap-shear specimens are investigated by three-dimensional finite element analyses. The computational stress intensity factor solutions for the realistic and idealized weld geometries obtained from two-dimensional plane strain finite element analyses are first reviewed. Further additional two-dimensional finite element analyses were carried out in order to obtain the computational stress intensity factor solutions for the realistic weld geometries with unequal sheet thicknesses. Next, the distribution of the stress intensity factor solutions for continuous idealized welds and discontinuous idealized welds were obtained by three-dimensional finite element analyses. Finally, some conclusions are made.

ANALYTICAL STRESS INTENSITY FACTOR SOLUTIONS

Analytical stress intensity factor solutions for continuous welds in lap-shear specimens with idealized weld geometries were presented in Amodeo and Pan [15]. For the analytical solutions presented, the geometry of the weld was idealized to a square shape that represents two joined beams. The protrusion and shape of the weld throat were not considered. A schematic of a lap-shear specimen near an idealized

weld is shown in Figure 1. Both the upper and lower sheets have the same thickness t . In the figure, the weld width is represented by w . F/b represents the lap-shear force per unit weld length applied along the interfacial surface. The weld metal is assumed to have the same elastic properties as those of the base metal.

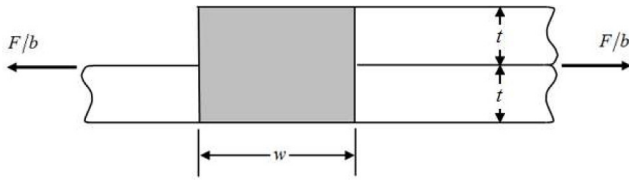


Figure 1. A schematic of a lap-shear specimen near an idealized weld.

The loading condition shown in Figure 1 gives different opening and shear modes of the crack. The K_I and K_{II} solutions can be derived from the elastic beam bending theory, as in Sripichai et al. [16], when w/t is large. The analytical stress intensity factor solutions for the lap-shear specimen are expressed as

$$K_I = \frac{\sqrt{3}}{2} \frac{F}{b\sqrt{t}} \quad (1)$$

and

$$K_{II} = \frac{F}{b\sqrt{t}} \quad (2)$$

The normalized equivalent stress intensity factor solution can be used for estimation of fatigue lives in a fatigue crack growth model under mixed mode loading conditions (Asim et al. [17]). The equivalent stress intensity factor under mixed mode loading conditions, K_e , can be defined as

$$K_e = \sqrt{K_I^2 + K_{II}^2} \quad (3)$$

TWO-DIMENSIONAL FINITE ELEMENT ANALYSES

Two-dimensional plane strain finite element analyses were carried out in order to obtain the computational stress intensity factor solutions for the pre-existing cracks between the upper and lower sheets near the roots of the continuous welds with idealized and realistic weld geometries. Computations were performed using the commercial finite element code ABAQUS Standard v611 [18]. The weld metal, heat affected zone, and base metal were assumed to be linear elastic with Young's modulus $E = 207$ GPa and Poisson's ratio $\nu = 0.3$. Second-order, continuum, plane strain elements (CPE8) were used in the models. The element size near the weld was about $150 \mu\text{m}$. A finer mesh was used near the pre-existing crack tip with the element size of $10 \mu\text{m}$ closest to the crack tip. The two-dimensional, plane strain finite element model was adopted from Amodeo and Pan [15].

Figure 2(a) shows a schematic of a two-dimensional finite element model of a lap-shear specimen with realistic weld geometry. The specimen has the upper sheet thickness t_u , lower sheet thickness t_l , overlap length g , weld width w , weld height h , and weld toe angle θ . The coordinate system is shown in the figure. The left edge has a fixed displacement condition at the upper surface while the right edge has a concentrated force per unit weld length F/b , applied at the lower surface in the +x direction.

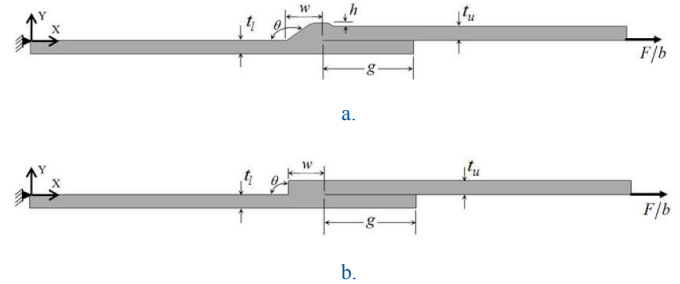


Figure 2. (a) A schematic of a two-dimensional finite element model of a lap-shear specimen with a realistic weld and the boundary conditions. (b) A schematic of a two-dimensional finite element model of a lap-shear specimen with an idealized weld and the boundary conditions.

The cross sectional geometry of the weld metal used to represent a realistic weld was designed to match the micrograph of the cross section of a lap-shear specimen studied in Amodeo et al. [1] and Amodeo and Pan [15]. The two-dimensional plane strain finite element model has the overlap length $g = 13.4$ mm, the weld width $w = 5.29$ mm, the weld height $h = 0.53$ mm, and the toe angle $\theta = 145^\circ$.

For comparison, finite element analyses were carried out in order to obtain the computational stress intensity factor solutions for the idealized weld. A schematic of a two-dimensional finite element model of a weld with idealized weld geometry is shown in Figure 2(b). Here, the weld toe angle θ is 90° and the weld height h is 0. The remaining parameters are kept the same as in the finite element models of the welds with the realistic weld geometries.

TWO-DIMENSIONAL COMPUTATIONAL STRESS INTENSITY FACTOR SOLUTIONS

In Amodeo and Pan [15], the normalized computational stress intensity factor solutions were obtained for lap shear specimens with equal upper and lower sheet thickness t . In order to obtain the stress intensity factor solutions for various realistic weld geometries, the sheet thickness in the finite element model was varied while keeping the overlap length, the weld width, the weld height, and the weld toe angle constant. For reference, the results are summarized in Table 1 and the conclusions are reviewed briefly here. All solutions shown in the table are normalized by the K_{II} solution based on the beam bending theory for an idealized weld geometry.

Table 1. The normalized stress intensity factor solutions for idealized and realistic weld geometries.

	Analytical Solution	FEA Result Idealized Geometry			FEA Result Realistic Geometry		
t (mm)	--	1.5	2.0	2.5	1.5	2.0	2.5
w/t	--	3.53	2.65	2.11	3.53	2.65	2.11
$\bar{K}_I$	0.87	0.87	0.86	0.83	0.74	0.74	0.72
$\bar{K}_{II}$	1.00	1.00	1.00	1.00	0.85	0.88	0.91
$\bar{K}_e$	1.32	1.32	1.32	1.30	1.12	1.15	1.17

As shown in Table 1, the normalized computational solutions for the idealized geometry match the analytical solutions for the given ratios of w/t well. The $\bar{K}_I$ and $\bar{K}_{II}$ solutions for the larger sheet thicknesses deviate slightly from the analytical solutions due to the lower value of w/t . The analytical solutions are derived from beam bending theory with the assumption that the weld width is much larger than the sheet thickness. The computational results indicate that the idealized geometry over estimates the stress intensity factor solutions. Table 1 also shows small variation in the stress intensity factor solutions for the ratios of w/t investigated in this study.

In this study, additional finite element analyses were carried out in order to obtain the computational stress intensity factor solutions for realistic welds with unequal sheet thicknesses. Lai et al. [19] presented the stress intensity factor solutions between two similar and dissimilar sheets with unequal thicknesses under plane strain conditions for ultrasonic welds. As presented in [19], the stress intensity factor solutions for welds joining sheets of identical materials with unequal sheet thicknesses can be written in the normalized forms as

$$\bar{K}_I^d = k_I(\delta) \frac{F}{b\sqrt{t_u}} \quad (4)$$

$$\bar{K}_{II}^d = k_{II}(\delta) \frac{F}{b\sqrt{t_u}} \quad (5)$$

and

$$\bar{K}_e^d = k_e(\delta) \frac{F}{b\sqrt{t_u}} \quad (6)$$

where k_p , k_{II} , and k_e are the dimensionless geometric functions for a given δ . These dimensionless geometric k_p , k_{II} , and k_e functions can also be viewed as the normalized stress intensity factor solutions. Here, δ is the ratio of the upper sheet thickness to the lower sheet thickness as

$$\delta = t_u / t_l \quad (7)$$

In this investigation, the thickness ratios modeled ranged from 0.2 to 5.0. The upper sheet thickness t_u is kept at 2.0 mm for the different thickness ratios. The selection of the geometries appears to be reasonable for δ less than 1. However, for completeness several values of δ larger than 1 are selected. Since there is only a small variation in the stress intensity factor solutions with the different ratios of w/t , the weld width w is kept at 5.29 mm for the different thickness ratios.

Figure 3 shows the dimensionless geometric functions k_p , k_{II} , and k_e as functions of the thickness ratio δ from the finite element analyses. As shown in the figure, the thickness ratio δ can have significant effects on the stress intensity factor solutions and their mode mixities. It should be noted that, the normalized equivalent stress intensity factor solution can be used for estimation of fatigue lives in a fatigue crack growth model under mixed mode loading conditions for gas metal arc welds with dissimilar sheet thicknesses.

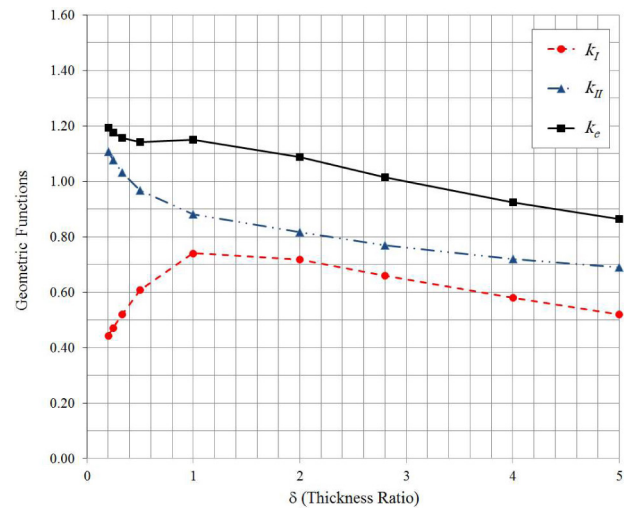


Figure 3. The dimensionless geometric functions as functions of the thickness ratio from the finite element analyses.

THREE-DIMENSIONAL FINITE ELEMENT ANALYSES

Three-dimensional finite element analyses were conducted in order to investigate the distributions of the stress intensity factor solutions along the fronts of the pre-existing cracks of continuous and discontinuous gas metal arc welds in lap-shear specimens. The mesh density used in the three-dimensional models was kept the same as that from the two-dimensional plane strain finite element model with the idealized weld geometry and the sheet thickness of 2.0 mm. First-order, continuum, hexahedral elements (C3D8) were used. As shown in Figure 2(b) for the idealized weld, the overlap length $g = 13.4$ mm, the weld width $w = 5.29$ mm, the weld height $h = 0$ mm, and the toe angle $\theta = 90^\circ$ were also kept the same as those from the two-dimensional plane strain finite element model with idealized weld geometry.

Figure 4(a) shows a schematic top view of a three-dimensional finite element model of a lap-shear specimen with continuous gas metal arc weld. The coordinate system is shown in the figure. The left edge has a fixed displacement condition at the upper surface while the right