

Fatigue Behavior of Laser Welds in Lap-Shear Specimens of High Strength Low Alloy (HSLA) Steels

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ABSTRACT

Fatigue behavior of laser welds in lap-shear specimens of high strength low alloy (HSLA) steels is investigated based on a fatigue crack growth model. Fatigue experiments of laser welded lap-shear specimens were conducted. Analytical global stress intensity factor solutions are developed and compared with finite element computational results. A fatigue crack growth model based on the analytical local stress intensity factor solutions of kinked cracks and the Paris law for crack growth is then adopted to estimate the fatigue lives of the laser welds under cyclic loading conditions. The estimated fatigue lives are compared with the experimental results. The results indicate that the fatigue life predictions based on the fatigue crack growth model are slightly longer than the experimental results. The results of the predictions indicate that consideration of the finite length of the kinked crack in the fatigue crack growth model is needed to predict the experimental results more accurately.

INTRODUCTION

Laser welding has been used more widely in the industry because of its advantages such as narrow heat affected zone, small residual stress and distortion, and relatively high welding speed. A lap joint is one of common weld joints in laser welding due to its relative less restricted tolerance requirement. Due to the geometry of a lap joint, natural cracks or notches are presented at the

edges of the weld bead. Fatigue cracks usually are initiated from the natural cracks or notches of lap joints. Laser welded components with lap joints are often subjected to cyclic loading conditions. Many researchers investigated the fatigue lives of laser welded lap joints. Hsu and Albright [1] combined a static stress analysis with the Neuber's rule and established a model to calculate the fatigue life from the local stress and strain near the main notch. Wang and Ewing [2] conducted experiments to examine the fatigue strengths for resistance spot welds and laser welds under lap-shear loading conditions. Flavenott et al. [3] performed fatigue tests on laser welded lap joints with various welding parameters such as weld bead geometry, the gap between the upper and lower sheets and the input energy of laser. Wang [4] correlated the experimental fatigue lives of laser welds with the values of the J -integral from finite element computations. Zhang [5] proposed structural stress solutions based on the outer surface strains of laser welded lap joints.

In order to analyze the experimental results for laser welded lap joints under cyclic loading conditions, a fracture mechanics approach is adopted here. Stress intensity factor solutions of laser welded lap joints are required for this approach. Pook [6] adopted the energy release rate concept to determine stress intensity factor solutions of various configurations with connections based on the simple beam/plate bending theory. Newman and Dowling [7] adopted Pook's global stress intensity factor solutions to develop a fatigue crack

growth model to predict the fatigue lives of spot welds. Lin et al. [8] adopted the fatigue crack growth model to model the kinked crack growth near spot welds in various types of specimens and correlated the predicted fatigue lives with the experimental results. Both Newman and Dowling [7] and Lin et al. [8] assumed the local stress intensity factors for kinked cracks to be constant for all kink lengths.

In this investigation, fatigue experiments of laser welded lap-shear specimens were conducted. The analytical global stress intensity factor solutions for the main cracks are developed based on the beam bending theory. Finite element computations were also carried out to obtain the global stress intensity factor solutions of the main cracks. The analytical global stress intensity factor solutions and global stress intensity factor solutions from finite element computations are adopted in the fatigue crack growth model with the assumption that the local stress intensity factors for kinked cracks are constant for all kink lengths. The predicted fatigue lives based on the fatigue crack growth model with experimentally determined kink angles are then compared with the experimental results. Finally, conclusions are made and future works are suggested.

EXPERIMENTAL RESULTS FOR LASER WELDS IN LAP-SHEAR SPECIMENS OF HSLA

Lap-shear specimens were made by using two 97 mm by 27 mm HSLA sheets with a thickness of 1 mm. The specimens were welded with 6 kW CO₂ laser with a weld speed of 8 m/min. The specimens were then cut into a dog-bone shape. Figures 1(a) and 1(b) show top and bottom views of a laser welded lap-shear specimen with the width of laser weld of 1 mm. The width and length of the uniform narrow part of the dog-bone area are 8 mm and 15 mm, respectively. Two doublers of 50 mm by 27 mm are used to align the applied load to avoid the initial realignment of the specimen under lap-shear loading conditions and to strengthen the gripping holes of the specimen. The lap-shear specimens were tested by using an Instron servo-hydraulic fatigue testing machine with a load ratio $R = 0.2$. The test frequency was 10 Hz. The tests were terminated when the displacement of the two grips of the specimen exceeded 10.16 mm. Under this displacement condition, specimens had broken to two pieces or were on the verge of failure. Figure 2 shows the experimental results of laser welded lap-shear specimens under cyclic loading conditions. Note that at the lowest load range of 822 N, the experiment was terminated when a million cycles was reached and the specimen did not fail. The specimen was counted as run out.

The failed specimens were then examined. Figure 3 shows a micrograph of a partially failed laser weld. Two fatigue cracks appear to be initiated near the main crack tips at the edges of the laser weld. The fatigue cracks can be considered as kinked cracks with respect to the original main crack tips. Note that for all specimens, the right kinked cracks grew faster through the upper sheets

of the specimens under cyclic loading conditions. Based on the experimental observations, the kink angles for both cracks are approximately 90°.

ANALYTICAL GLOBAL STRESS INTENSITY FACTOR SOLUTIONS

Figure 4 shows a schematic diagram of a lap-shear specimen. As shown in the figure, the specimen has the width W , the sheet thickness t , and the length L for the upper and lower sheets. The specimen was made with a dog-bone shape. The specimen has the width b for the central portion of the dog-bone area, the overlap length V and the width w of the laser weld zone, which is indicated as the shaded area. The total applied force F is shown as the bold arrows. Similar to Pook [6], for a 2-D plane-strain analysis, the simple beam bending theory is adopted to derive the analytical stress intensity factor solutions. The laser weld zone is assumed to have the same elastic properties as the base metal.

As in Radaj [9], Radaj and Zhang [10-12], and Lin et al. [13,14], the load of a lap-shear specimen can be decomposed into statically equivalent symmetric and anti-symmetric loads. Figure 5 shows a schematic diagram of the decomposition of the shear load of a lap-shear specimen. Here, the dog-bone area of a lap-shear specimen is modeled as two beams with a connection. For the two beams shown in Figure 5(a), F/b represents the force per unit width of the dog-bone area. The forces F/b are applied along the interfacial surface of the two beams. In Figure 5(b), the forces F/b now become the membrane forces per unit width, F/b , and the bending moments per unit width, $Ft/2b$, applied at the middle of the upper and lower beams. Both applied membranes forces and bending moments shown in Figure 5(b) are statically equivalent to the shear forces of the two beams shown in Figure 5(a). The membrane forces and bending moments in Figure 5(b) can further be decomposed into four types of symmetric and anti-symmetric loading conditions: counter bending (Figure 5(c)), central bending (Figure 5(d)), tension (Figure 5(e)) and in-plane shear (Figure 5(f)). The bending moments per unit width in counter bending and central bending loading conditions have a magnitude of $Ft/4b$ and the forces per unit width in tension and in-plane shear loading conditions have a magnitude of $F/2b$.

Four types of loading conditions in Figure 5 give different opening and shear modes of the main crack. The counter bending loading condition gives a mode I (opening mode) loading to the main crack while the central bending and in-plane shear loading conditions give a mode II (in-plane shear mode) loading to the main crack. Thus, the K_I solution can be derived from the two beams in the counter bending loading condition (Figure 5(c)), while the K_{II} solution can be derived from the two beams in the central bending and in-plane shear loading conditions (Figure 5(d) and 5(f)). The tension loading condition (Figure 5(e)) does not give any

global stress intensity factor solutions. The K_I stress intensity factor solution is determined from the counter bending loading condition as

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

Similarly, the K_{II} stress intensity factor solution is determined from the central bending and in-plane shear loading conditions based on the superposition principle as

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

The detailed derivation of Equations (1) and (2) will be presented in [15]. Equations (1) and (2) were derived based on the assumption that the weld width w is large compared to the thickness t of the upper and lower sheets. The validation of this assumption will be examined by a finite element analysis that is presented in the following.

COMPUTATIONAL GLOBAL STRESS INTENSITY FACTOR SOLUTIONS

A finite element analysis was also carried out in order to obtain the global stress intensity factor solutions to compare with the analytical solutions. Figure 6(a) shows a schematic diagram of a two-dimensional finite elemental model of a lap-shear specimen and the boundary conditions. The specimen has the sheet thickness t , the length L , the overlap length V and the width w of the laser weld zone. Both upper and lower sheets have the same thickness t . The $x-y$ coordinate system is shown in the figure. The left edge surface has a clamped boundary condition while the right edge surface has a concentrated force per unit width of F/b applied at the middle of the thickness in the $+x$ direction. Here, F denotes the total applied force and b denotes the width of the central portion of the dog-bone area of the specimen.

The two-dimensional plane-strain finite elemental model is developed with the weld width $w=1$ mm, sheet thickness $t=1$ mm, length $L=87$ mm, and overlap length $V=15$ mm. The width b of the central portion of the dog-bone area of the specimen used in the model is 8 mm. Note that the length L is taken between the left edge and the center of the hole of the upper sheet as shown in Figure 1. The displacement in the x and y directions are constrained to represent the clamped boundary condition for the left edge of the specimen. Figures 6(b) and 6(c) show the right part of the finite element mesh and a close-up view of the mesh near the main crack tip, respectively. The weld metal and the base metal are assumed to be linear elastic with the Young's modulus $E=210$ GPa and the Poisson's ratio

$\nu=0.3$. Second-order quarter point crack-tip elements with collapsed nodes and mid-side nodes moved to $1/4$ points were used to model the $1/\sqrt{r}$ singularity near the crack tip. The commercial finite element program ABAQUS [16] is employed to perform the computation.

The values of the global K_I and K_{II} are obtained and normalized by the global K_I and K_{II} solutions based on the beam bending theory in Equations (1) and (2), respectively. The value of the normalized global K_I is 0.51 and the value of the normalized global K_{II} is 1.03. These values indicate that the analytical global K_I solution based on the beam bending theory is approximately two times higher while the analytical global K_{II} solution agrees well with the computational result. Further research on the global K_I and K_{II} solutions will be carried out to investigate the effects of the weld geometry on the global stress intensity factor solutions.

ANALYTICAL LOCAL STRESS INTENSITY FACTOR SOLUTIONS FOR KINKED CRACKS

Figure 7 shows a schematic of a main crack and a kinked crack with the kink length a and the kink angle α . Here, K_I and K_{II} represent the global stress intensity factors for the main crack, and k_I and k_{II} represent the local stress intensity factors for the kinked crack. Note that the arrows in the figure represent the positive values of the global and local stress intensity factors K_I , K_{II} , k_I and k_{II} .

For kinked cracks, when the kink length approaches to 0, the local stress intensity factors k_I and k_{II} can be expressed as functions of the kink angle α and the global K_I and K_{II} for the main crack. The local $(k_I)_0$ and $(k_{II})_0$ solutions are given as (Billby et al. [17] and Cotterell and Rice [18])

$$(k_I)_0 = \frac{1}{4} \left(3 \cos \frac{\alpha}{2} + \cos \frac{3\alpha}{2} \right) K_I - \frac{3}{4} \left(\sin \frac{\alpha}{2} + \sin \frac{3\alpha}{2} \right) K_{II} \quad (3)$$

$$(k_{II})_0 = \frac{1}{4} \left(\sin \frac{\alpha}{2} + \sin \frac{3\alpha}{2} \right) K_I + \frac{1}{4} \left(\cos \frac{\alpha}{2} + 3 \cos \frac{3\alpha}{2} \right) K_{II} \quad (4)$$

where $(k_I)_0$ and $(k_{II})_0$ represent the local k_I and k_{II} solutions for the kink length a approaching to 0. Since the fatigue crack growth is under local combined mode I and II loading conditions, the range of the equivalent stress intensity factor, Δk_{eq} can be defined as

$$\Delta k_{eq} = \sqrt{(\Delta k_I)_0^2 + \gamma (\Delta k_{II})_0^2} \quad (5)$$