

Fatigue Failure of Laser Welds in Lap-Shear Specimens of High Strength Low Alloy (HSLA) Steels under Cyclic Loading Conditions

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ABSTRACT

In this paper, the fatigue behavior of laser welds in lap-shear specimens of non-galvanized SAE J2340 300Y high strength low alloy (HSLA) steel sheets is investigated based on experimental observations and a fatigue life estimation model. Optical micrographs of the laser welds before and after failure under quasi static and cyclic loading conditions are examined. The micrographs show that the failure modes of laser welds under quasi-static and cyclic loading conditions are quite different. Under quasi-static loading conditions, the weld failure appears to be initiated from the base metal near the boundary of the base metal and the heat affected zone at a distance to the pre-existing crack tip, and the specimens fail due to the necking/shear of the lower left load carrying sheets. Under low-cycle loading conditions, the weld failure appears to be initiated from the pre-existing crack tips and the specimens finally fail from the ductile fracture through the lower left load carrying sheets. Under high-cycle loading conditions, the weld failure appears to be initiated from the pre-existing crack tips and the specimens finally fail from the kinked fatigue crack propagating through the upper right load carrying sheets. Finite element analyses of the laser welded lap-shear specimens with consideration of the weld bead protrusion were carried out to obtain the global and local stress intensity factor solutions for the main cracks and kinked cracks, respectively. A kinked fatigue crack growth model based on the global and local stress intensity factor solutions for finite kinked cracks obtained from the finite element analyses is adopted to estimate the fatigue lives of the laser welds. The fatigue life estimations based on the kinked fatigue crack growth model agree well with the experimental results.

INTRODUCTION

Laser welding has many advantages over the conventional welding methods. These advantages include relatively low distortion of the weld, narrow heat affected zone, relatively high welding speed and high penetration. Over the past two decades, extensive research efforts have been spent on studying the fatigue behavior of laser welds for different materials and joint configurations. Lap joints have been commonly used to assess the strength and fatigue behavior of laser welds under shear dominant loading conditions. The geometry of a lap joint provides pre-existing cracks or notches at the edges of the weld bead. Therefore, the fatigue cracks were usually observed to be initiated from these stress concentration sites.

Hsu and Albright [1] combined a static stress analysis and Neuber's rule to predict the fatigue lives of laser welded lap joints. Wang and Ewing [2] compared the fatigue strengths of laser welds and resistance spot welds in lap-shear specimens of steel sheets on the basis of equal weld volume. They reported that the fatigue failure in laser welds is dominated by crack propagation in the heat affected zone. Flavenot et al. [3] performed an experimental study to examine the influence of laser beam type, weld bead geometry, gap between the sheets and the input energy on the fatigue behavior of laser welded lap joints. Wang [4] correlated the experimental fatigue lives of laser welds in lap-shear specimens with the values of the J integral obtained from finite element analyses. The results were also used to assess the influence of parameters such as the weld geometry, sheet thickness, bead width, metal fit-up and bead length. Ono et al. [5] investigated the static and fatigue strengths of laser welded lap joints of thin steel sheets and correlated the fatigue lives of laser welded lap joints with the maximum stress intensity factor ranges. Sripichai et al.

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[6] recently investigated the fatigue behavior of laser welds in lap-shear specimens of high strength low alloy steel sheets based on the closed-form and computational stress intensity factor solutions.

In this study, the fatigue behavior of laser welds in lap-shear specimens of non-galvanized SAE J2340 300Y HSLA steel sheets is investigated based on experimental observations and a fatigue life estimation model. Optical micrographs of the welds before and after failure under quasi-static and cyclic loading conditions are examined to investigate the microstructure and failure mechanisms of the welds. Scanning electron micrographs of the failure surfaces are also used to explain the failure modes of laser welds in lap-shear specimens under quasi-static and cyclic loading conditions. Finite element analyses of the laser welded lap-shear specimens with consideration of the weld bead protrusion were carried out to obtain the global and local stress intensity factor solutions for the main cracks and kinked cracks, respectively. A kinked fatigue crack growth model based on the global and local stress intensity factor solutions for finite kinked cracks obtained from the finite element analyses is adopted to estimate the fatigue lives of the laser welds. Finally, the estimated fatigue lives based on the kinked fatigue crack growth model are compared with the experimental results.

EXPERIMENT

HSLA steel sheets with a thickness of 0.93 mm were used in this investigation. The mechanical properties obtained from the tensile tests of the HSLA steel sheets are listed in Table 1. The sheets were welded using CO₂ laser with an output power of 6KW. The welded sheets were machined into specimens with a dog-bone shaped profile using a CNC milling machine according to the guidelines provided in the ANSI/AWS B4.0:2007 standard for mechanical testing of welds and the ASTM E466-07 standard for conducting force controlled constant amplitude axial fatigue tests of metallic materials. Figures 1(a) and 1(b) show top and bottom views of a laser welded lap-shear specimen, respectively.

Table 1. Mechanical properties from the tensile tests of HSLA base metal sheets.

Elastic Modulus (GPa)	Yield Stress (MPa)	Tensile Strength (MPa)	Hardening Exponent n	Strength Coefficient K (MPa)
206	315	415	0.15	633

Figure 2 shows a schematic of a lap-shear specimen. As shown in the figure, the specimen has a width W , sheet thickness t , and length L for the upper and lower sheets. The specimen has a width b and a length c for the central portion of the specimen, an overlap length V and a width w for the weld zone, which is indicated as the shaded region in the

figure. Two doublers were used to align the applied load to avoid the initial realignment of the specimen under lap-shear loading conditions. The doublers have a length s and a width W . The detailed dimensions of the lap-shear specimen are listed in Table 2. The loading direction is indicated by two bold arrows on the left and right sides of the specimen in the schematic. These bold arrows are used to indicate the loading directions in the subsequent figures.

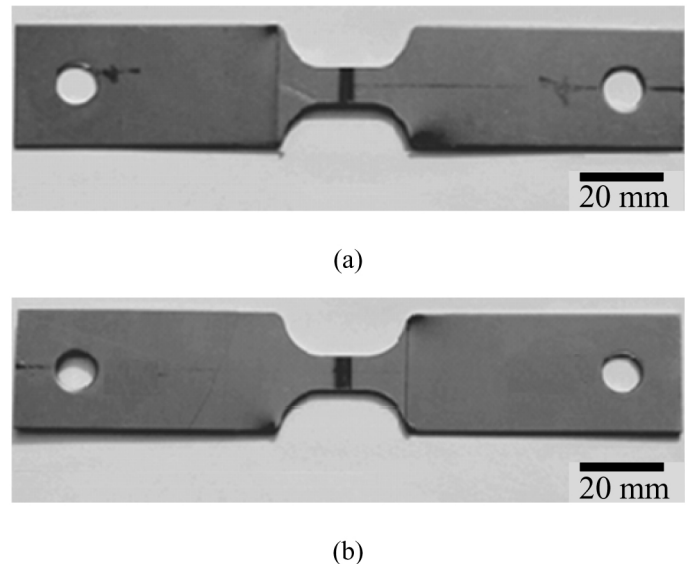


Figure 1. (a) A top view and (b) a bottom view of a laser welded lap-shear specimen.

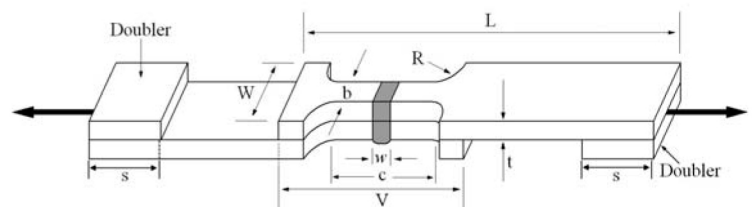


Figure 2. A schematic of a lap-shear specimen with the loading direction shown as the bold arrows.

Table 2. Dimensions of the lap-shear specimen.

Grip section width (W)	27.0 mm
Central portion width (b)	8.0 mm
Central portion length (c)	13.5 mm
Weld width (w)	1.0 mm
Leg length (L)	95.0 mm
Overlap length (V)	30.0 mm
Sheet thickness (t)	0.93 mm
Radius (R)	9.5 mm
Doubler length (s)	50.0 mm

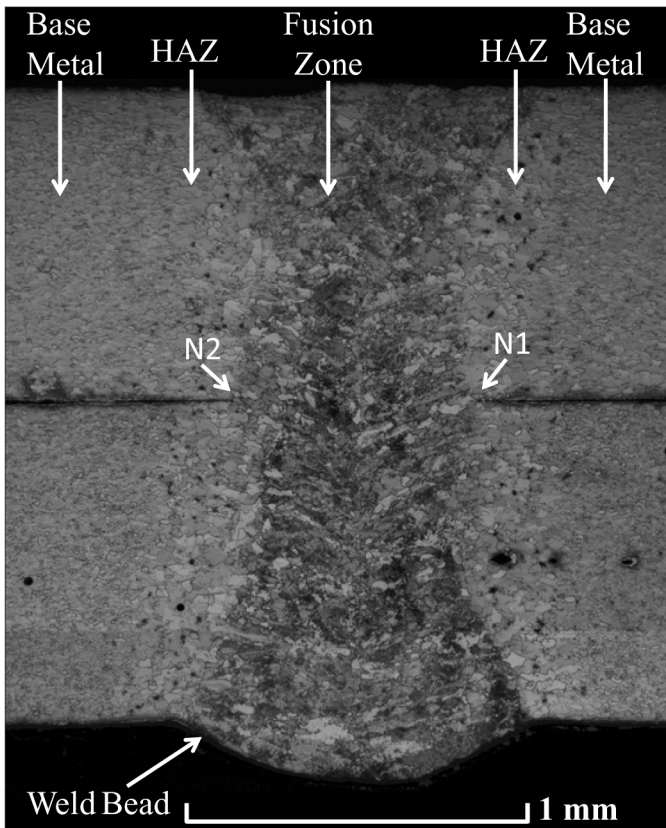


Figure 3. An optical micrograph of the etched cross section of a laser weld in a lap-shear specimen perpendicular to the welding direction.

Figure 3 shows an optical micrograph of the etched cross section of a laser weld in lap-shear specimen perpendicular to the welding direction before testing. Based on their distinct grain structures, three separate regions can be identified from the micrograph, namely, the base metal, the heat affected zone (HAZ) and the fusion zone. The width of the fusion zone, as seen from the micrograph in Figure 3, is about 0.80 mm along the middle surface of the weld between the two pre-existing cracks. The two pre-existing cracks tips which are formed by joining the two steel sheets have been identified as N1 and N2 in the figure. The micrograph in Figure 3 also shows that the weld is free of porosities and other welding defects such as cracks and voids.

Lap-shear specimens were first tested under quasi-static loading conditions by using an automated MTS testing machine equipped with a load cell and a built-in position sensor to track the movement of the cross-head. The cross-head speed was maintained constant at 1 mm/min during these tests. The load and displacement histories were simultaneously recorded during each test. The average failure or maximum load, defined as the average of the maximum loads of the load-displacement curves, obtained from the quasi-static tests of five lap-shear specimens was about 3.1 kN. This failure load was used as the reference load to

determine the applied load ranges in the fatigue tests. The average maximum displacement obtained from these tests was about 2.16 mm. The average failure load and displacement were used as the reference values to set the machine loading limits for the fatigue tests.

Lap-shear specimens were tested under cyclic loading conditions by using an Instron servo-hydraulic fatigue testing machine with the load ratio $R = 0.2$. A sinusoidal loading profile was chosen and its frequency was set at 10 Hz during the tests. The test was considered to be completed at the final separation of the welded sheets. A few tests were interrupted before the final separation to study the fatigue crack growth patterns. The fatigue tests were terminated when specimens were subjected to one million loading cycles without separation and recorded as a run-off. The specimens failed under cyclic loading conditions were sectioned perpendicular to the welding direction using a low speed diamond saw and prepared for micrographic analyses. Etching of the cross sections was carried out using a 5% Nital solution. The failure surfaces of the failed specimens were also examined under a scanning electron microscope.

FAILURE MODES OF LASER WELDS UNDER QUASI-STATIC AND CYCLIC LOADING CONDITIONS

The results of the present study show that all laser welds failed in the base metal under quasi-static loading conditions and in the HAZ under cyclic loading conditions. The failure mode of laser welds in lap-shear specimens depends on the applied load ranges, and the failure location can change from the lower left sheet under low-cycle loading conditions to the upper right sheet under high-cycle loading conditions. Note that the definitions of low-cycle and high cycle fatigue loading conditions in this study are only provided for convenient presentation.

FAILURE MODE UNDER QUASI-STATIC (QS) LOADING CONDITIONS

Figure 4(a) shows an optical micrograph of the etched cross section of a failed weld in a lap-shear specimen under quasi-static loading conditions. The upper right and lower left sheets were the two load carrying sheets in these tests. The loading direction is schematically shown by the bold arrows in the figure. The dominant failure mode of the lap-shear specimens under quasi-static loading conditions is the necking/shear of the lower left sheet. The ductile failure was initiated in the base metal near the boundary of the base metal and HAZ and the lower left sheet was then separated from the weld as shown in Figure 4(a). Figure 4(b) shows a scanning electron micrograph of the failure surface of the lower left sheet of a failed specimen under quasi-static loading conditions. The white vertical arrow in the micrograph