

Modeling of Failure Modes of Gas Metal Arc Welds in Notched Lap-Shear Specimens of HSLA Steel

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ABSTRACT

The failure modes of gas metal arc welds in notched lap-shear specimens of high strength low alloy (HSLA) steel are investigated. Notched lap-shear specimens of gas metal arc welds were first made. Quasi-static test results of the notched lap-shear specimens showed two failure locations for the welds. The specimens cut from coupons with shorter weld lengths failed near the weld root whereas the specimens cut from coupons with longer weld lengths failed near the weld toe. Micro-hardness tests were conducted in order to provide an assessment of the mechanical properties of the base metal, the heat affected zone, and the weld metal. In order to understand the failure modes of these welds, finite element models were developed with the geometric characteristics of the weld metals and heat affected zones designed to match those of the micrographs of the cross sections for the long and short welds. Three-dimensional finite element analyses were conducted with consideration of micro void nucleation and growth. The distributions of the void volume fraction and the necking modes near the welds shown from the finite element analyses correlate well with the failure modes observed in the experiments.

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INTRODUCTION

Recently, many investigations on the 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]. For the automotive industry, the performance of discontinuous gas metal arc welded joints is of significant interest. By minimizing the length of the discontinuous welds, significant cost savings can be gained due to reduced cycle time and reduced usage of equipment and consumables. However, improperly sized welds can result in the loss of structural integrity near the welds in service.

In this paper, the effects of weld geometries and the mechanical properties of discontinuous gas metal arc welded joints of HSLA340 steel on the failure modes of notched lap-shear specimens are investigated under quasi-static loading conditions. For lack of further information, the residual stresses due to the welding process are not considered in this investigation. Notched lap-shear specimens were cut from the middle sections of the wide lap-shear specimens of various discontinuous weld lengths. Quasi-static tests were conducted in order to determine the failure modes of the welds. Three-dimensional finite element analyses were also conducted with

consideration of micro void nucleation and growth. The locations of the highest void volume fractions and the necking modes from the finite element analyses are compared to those of the failed specimens observed in experiments. Finally, conclusions are made.

EXPERIMENTS

Notched Lap-Shear Specimens

In this investigation, lap-shear specimens of HSLA steel sheets with a thickness of 2.0 mm were robot welded together using the gas metal arc weld process. A filler metal of ER70S-6 with 0.035 inch wire diameter was used. The short circuit metal transfer mode was used with 75% argon and 25% carbon dioxide shielding gas. The weld travel speed was 55 cm/min and the power settings were 125 A and 22.5 V. No heat treatment was carried out after the welding process. The grade of the steel sheets was SAE J2340 340XF. The chemical composition of the steel sheets was measured using spectrochemical analysis. This test was conducted using a Leco SA-2000 Surface Analyzer. The chemical composition is given in [Table 1](#).

Table 1. Chemical composition (wt %) of the SAE J2340 340XF steel sheets.

C	Mn	Si	P	S	Cr	Ni	Mo
0.055	0.563	0.028	0.008	0.0045	0.014	0.014	0.002
Cu	V	Al	Ti	Nb	B	Pb	Mg
0.0172	0.001	0.046	0.001	0.0187	0	0.0013	0.0003

In this investigation, 60 mm wide sheet specimens with the weld lengths varying from 10 mm to 40 mm were made. Some of these specimens are shown in Figure 1(a). In order to investigate the failure mechanism in the vicinity of the welds, and to avoid the failure of the specimen due to the necking of the specimen sheets far away from the welds, notched specimens were machined from the middle portions of the wide welded specimens using a CNC milling machine. Figure 1(b) shows a schematic of a notched lap-shear specimen. The weld zone is schematically indicated as the shaded area in the figure. As shown in the figure, the specimen has a width w of 15 mm outside of the central portion. The specimen has a length c of 13 mm for the central notched portion and a length d of 25 mm outside of the notch portion. The specimen has a minimum width b of 6 mm at the center of the notch. The radius of the notch is 7 mm. The specimen has a thickness t of 2.0 mm. Two doublers were used for aligning the applied load through the interfacial plane of the two sheets of the specimen. The loading direction is indicated by two bold arrows on the right and left sides of the specimen.

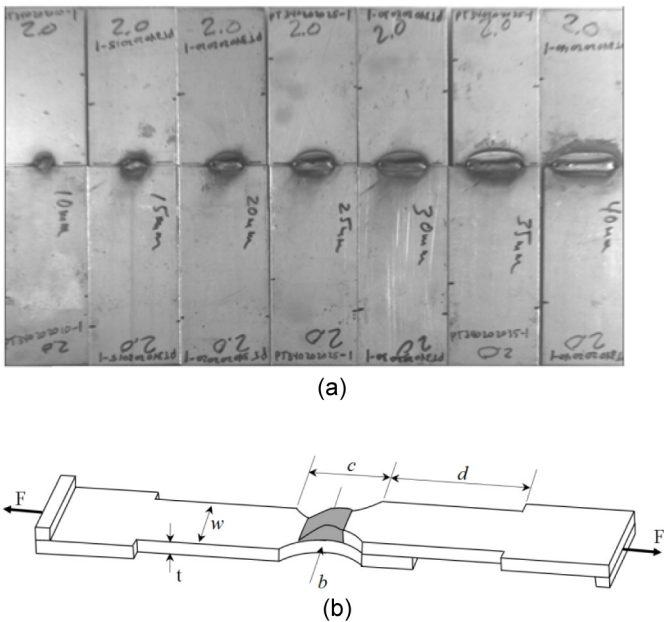


Figure 1. (a) Wide lap-shear specimens with the weld length varying from 10 mm to 40 mm. (b) A schematic of a notched lap-shear specimen that was machined from the middle portion of a wide welded specimen shown in (a).

Quasi-Static Test of the Notched Lap-Shear Specimens

Quasi-static tests of the notched lap-shear specimens were carried out under displacement controlled conditions. These tests were conducted using an Instron testing machine at a constant cross-head speed of 25 mm/min. Seven specimens, cut from wide lap-shear specimens of different weld lengths, were tested. An extensometer, with an initial gauge length of 2 inches, was used to measure the change in length of each specimen. The extensometer was centered on the test specimen. As referring to Figure 1(b), the right end of the bottom sheet of the lap-shear specimen was trimmed in order to avoid interference with the extensometer. Doublers were included within the grips to align the applied load through the interfacial plane of the two sheets of the specimen.

Table 2. Summary of results of the quasi-static tests

Specimen	Peak Load (N)	Fracture Location
S1-10	8262	Weld Root
S2-15	8943	Weld Root
S3-20	7889	Weld Root
S4-20	8723	Weld Toe
S5-30	7993	Weld Toe
S6-30	8247	Weld Toe
S7-40	8214	Weld Toe

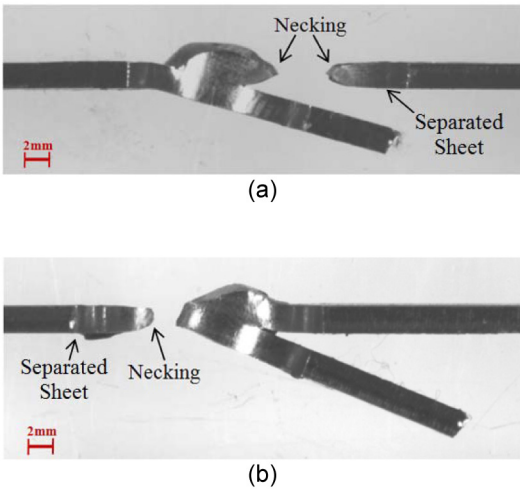


Figure 2. (a) A failed specimen machined from a wide specimen with a weld length of 10 mm and (b) a failed specimen machined from a wide specimen with a weld length of 30 mm.

Test results are summarized in Table 2. The specimens are labeled with a specimen number followed by the length of the discontinuous weld on the wide lap-shear specimen from which the notched specimen was cut. The welded specimens exhibited two competing failure locations. The specimens machined from wide lap-shear specimens with shorter weld lengths failed near the weld root. Figure 2(a) shows a side view

of the failed specimen S1-10 near the failure location. The specimens machined from wide lap-shear specimens with longer weld lengths failed near the weld toe. [Figure 2\(b\)](#) shows a side view of the failed specimen S5-30 near the failure location. The necking failure mode can be observed at both failure locations. The average maximum loads obtained from the specimens that failed near the weld root and from those that failed near the weld toe were 8.36 kN and 8.29 kN, respectively.

Weld Geometry and Micro-Hardness of Welded Joints

Micro-hardness tests were carried out in order to understand the Vickers hardness values in the weld region for specimens with short and long welds. Three specimens with different weld lengths were sectioned at the mid-sections of the welds. The specimens were cross sectioned, mounted, polished, and lightly etched to better visualize the heat affected zone and base metal boundaries. 2% nital solution was used as the etchant. Micro-hardness indentations were made with a 500 grams load and the indentations were carried out at an interval of about 350 μm . Results of the micro-hardness tests are shown in [Figure 3](#). The figure shows that the hardness in the heat affected zone and the weld metal becomes higher as the weld length becomes smaller. The figure also shows the trend in the size of the heat affected zone. The heat affected zone in the 10 mm weld extends past the toe of the weld as labeled A in the figure. The heat affected zone in the 40 mm weld does not reach the toe of the weld as labeled B in the figure.

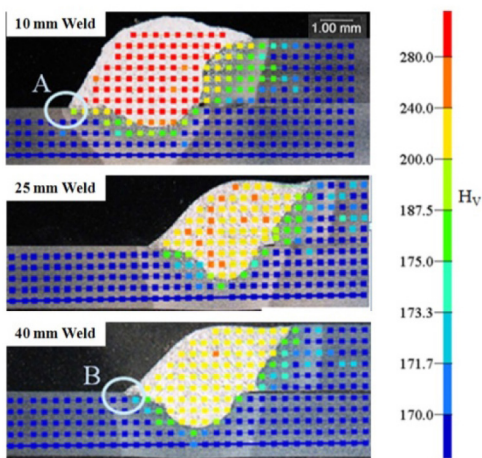


Figure 3. The Vickers hardness values in the weld region for specimens with short and long welds. The indentations were carried out at an interval of about 350 μm .

FINITE ELEMENT ANALYSES

Finite Element Models

Finite element analyses, based on the initial weld geometries, were carried out in this study in order to identify the influences of the weld geometry as well as the plastic behavior near the weld on the failure modes of the welds in lap-shear specimens.

Since the notched specimens are used to study the failure mechanism in the vicinity of the welds, three-dimensional finite element models were developed. In order to reduce the computational time, only a half of the specimen is modeled with the symmetry conditions applied at the mid-section of the weld. Second-order, continuum, hexahedral elements (C3D20) are used in the models. The element size near the weld is about 150 μm . Computations were performed using the commercial finite element code ABAQUS Standard v6.11 [10, 11, 12].

In order to identify the plastic behavior near and in short welds and long welds, two finite element models were developed. The sizes and shapes of the weld metals and the heat affected zones were designed to match those of the micrographs of the cross sections for the 10 mm weld (short weld model) and the 40 mm weld (long weld model) shown in [Figure 3](#). The location of the notch along the length of the specimen was centered near the geometric center of the weld metal. The base metal, the heat affected zone, and the weld metal can be identified based on their distinct grain structures and corresponding micro-hardness values. Based on the grain structures and the micro-hardness measurements shown in [Figure 3](#), the heat affected zone is sectioned into three distinct zones for the short weld model and two distinct zones for the long weld model. The finite element meshes near the weld for the short weld model and for the long weld model are shown in [Figures 4\(a\)](#) and [4\(b\)](#) with the different material sections, respectively.

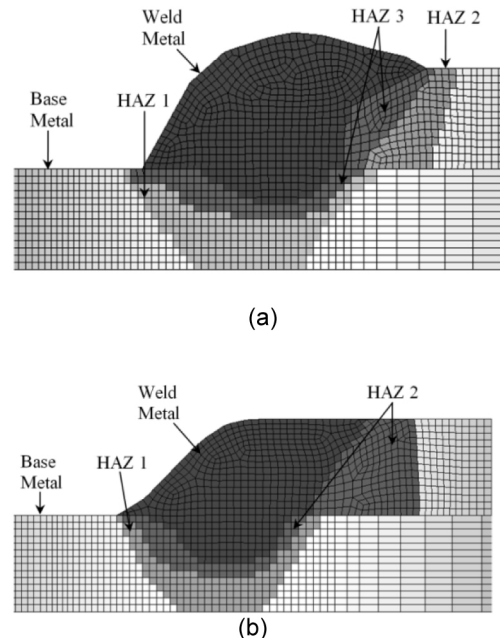


Figure 4. The finite element meshes near the weld for (a) the short weld model and (b) the long weld model with the different material sections.

Material Stress-Strain Curves

In order to obtain the stress-strain behavior of the base metal for use in the finite element models, tensile tests were performed according to the ASTM standard for a rectangular