

Ductile Fracture from Spot Weld and Flange Edge in Advanced High Strength Steels

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ABSTRACT

A simple testing method is proposed in order to investigate ductile fracture in crashed automotive components made from advanced high strength steels. This type of fracture is prone to occur at spot-welded joints and flange edges. It is well known that the heat affected zone (HAZ) is a weak point in high strength steel due to the formation of annealed material around the spot-welded nugget, and the flange edge also has low ductility due to the damage caused by shearing. The proposed method is designed to simulate a ductile fracture which initiates from a spot-welded portion or a sheared edge in automotive components which are deformed in a crash event. Automotive steel sheets with a wide range of tensile strengths from 590MPa to 1470MPa are examined in order to investigate the effect of material strength on fracture behavior. The effects of material cutting methods, namely, machining and shearing, are also investigated. A digital imaging strain analysis system is applied into the fracture test to analyze the strain distribution at the spot weld and the flange edge. The experimental results indicate the criterion for fracture in spot-welded specimens. Based on the experimental results, a FE simulation is carried out considering the change in material properties of the heat-affected material around spot weld. The FE simulation showed good agreement with the experimental results in the force-stroke curve and the strain history around the spot weld. Further study is expected to improve the accuracy of the fracture prediction based on the experimental results obtained by the proposed simple experimental method.

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INTRODUCTION

Achieving an optimized combination of crash safety performance and a lightweight structure has been an important challenge in automotive body engineering. Applications of high strength steels to auto body structures have been considered as an effective solution to this problem, which is feasible at relatively low cost in volume production in the automotive industry [1, 2, 3]. High strength steels must provide not only higher strength but also sufficient formability in the press stamping processes. The strength of steel materials have traditionally been limited to 440MPa considering the formability of automotive parts. Recently, advanced high strength steels with improved formability have been developed by optimizing the metallic microstructures [4]. As a result, advanced high strength

steels with strengths over 590MPa are now widely used in crucial parts for safety performance. Moreover, the range of applications of high strength steels in auto body structures is expanding, and ultra-high strength steels with strengths ranging from 980MPa to 1470MPa have been developed considering the optimum balance of material strength and formability [5].

While advanced high strength steels both reduce body weight and improve crashworthiness [6, 7], fracture of these materials in a crash event has been a critical issue for the reliable design of structural components. High strength steels are often more prone to necking or failure in crash deformation than conventional mild steels because the elongation of the steel decreases as its strength increases [8, 9, 10]. In

addition, spot-welded joints are a relatively weak point in high strength steel parts. Fracture is prone to initiate from spot-welded joints, and the initial fracture then extends over a large area in the body part [11, 12, 13]. Figure 1 shows an example of a fracture from a spot-weld and flange edge in an automotive component.

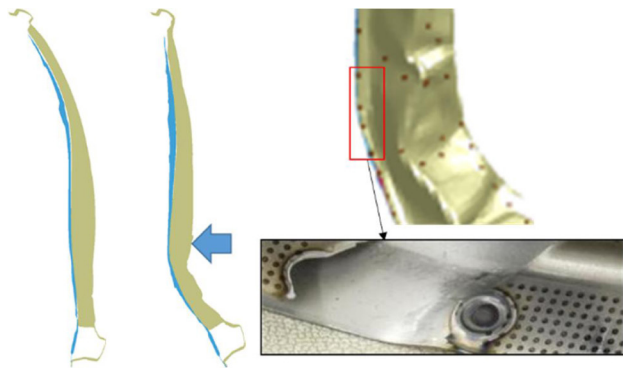


Figure 1. Example of a fracture from spot weld and edge in body part in case of severe crash deformation.

In optimization of materials and structures in body components, the finite element method (FEM) has been considered a powerful tool for estimating crash performance. However, continual study and improvement of the material models used in the numerical simulations is still needed due to the ever-increasing demands for more accurate predictions of deformation and material failure [14, 15, 16].

In this study, static bending tests and tensile tests were carried out by using a strain measurement system with digital images to investigate the fracture behaviors of spot-welded parts. The parts were made of a variety of steel sheets with tensile strengths from 590MPa to 1470MPa. The material thicknesses was 1.6mm considering the typical thickness of steel sheets used in automotive parts. These experiments clarified the effects of the material strength and the shearing condition on fracture behavior. The strain criterion for fracture of spot welds was investigated by using the strain measurement results with the aim of understanding the fracture behavior of spot-welded parts. A FE simulation was also demonstrated as a tool for simulating the fracture of spot-welded specimens.

EXPERIMENTAL PROCEDURE

Materials

In these experiments, several grades of sheet steels were selected in order to investigate the effect of material properties on fracture behavior. Table 1 shows the mechanical properties of the steel sheets used in this study. The mechanical properties, including yield strength, tensile strength and elongation, were examined by static tensile tests based on the applicable Japan Industrial Standard (JIS). The geometry of the specimen used in the tests had a gauge length of 50mm and a width of 25mm. The tensile tests were performed with a

constant velocity of 10mm/min. The material thicknesses of 1.6mm was selected considering the steel sheets commonly used in automotive body structures. Steel grades (indicated by the tensile strength) are also listed in Table 1. Steel sheets with a wide range of tensile strengths from 590MPa to 1470MPa were selected for the study. The steels with tensile strengths from 590MPa to 980MPa have a dual-phase micro-structure consisting of a soft ferrite phase and a hard martensite phase. The 1470MPa steel is a full-martensite steel, which is the highest strength steel currently used in commercial steel sheets for automotive applications.

Table 1. Mechanical properties of high strength steels measured by JIS tensile test protocol.

No.	Steel grade	Thickness (mm)	YS (MPa)	TS (MPa)	E1 (%)
1	590MPa	1.6	383	633	33
2	780MPa	1.6	543	814	22
3	980MPa	1.6	691	1015	17
4	1470MPa	1.6	1267	1496	8

Strain Measurement Method

A digital imaging strain analysis system was developed based on the computer vision principle [17] illustrated in Figure 2. Two digital cameras were installed in a tensile testing machine to measure the strain distribution during the tensile tests. Figure 3 (a) shows the two-camera system for static tensile testing with computer-controlled digital cameras. Figure 3 (b) shows the specifications of the digital camera. Dots with a diameter of 0.5 mm were printed with a pitch of 1 mm on specimens by the electrolytic etching method shown in Figure 3 (c). Although the smaller pattern is better for the strain measurement, the size of the dots was determined based on the limitation of etching precision. The center of the grid was determined by fitting the elliptic curves for each image shown in Figure 4. Using this method, the center of the distorted dots was determined accurately for the large deformation after the strain localization. The 3D coordinate points of the dots on the specimen were calculated using the center of the fitted ellipses. The strain distribution was calculated by tracking the 3D reconstructed points during tensile tests.

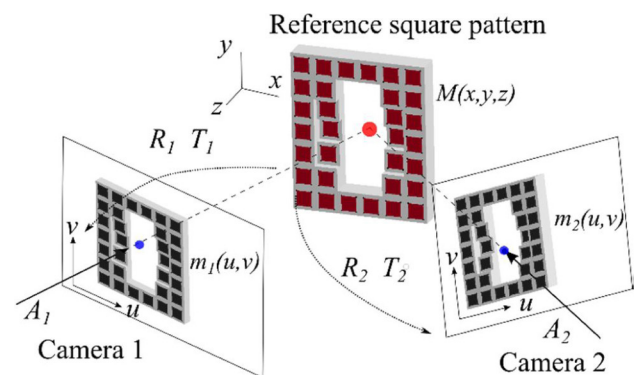


Figure 2. Rotation and translation of the stereo camera model [17].

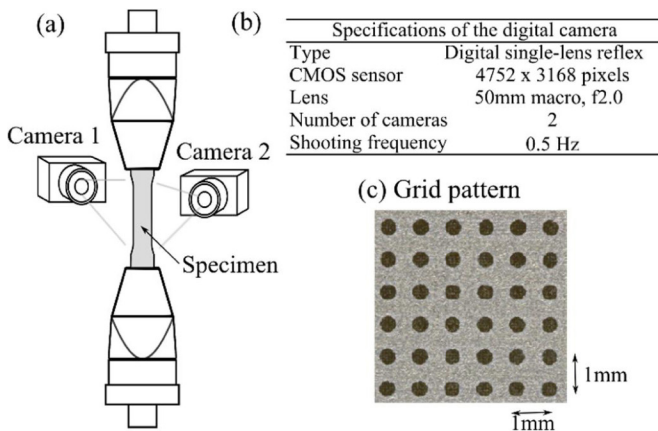


Figure 3. Measuring system of digital image grid method: (a) Static tensile test machine with two digital cameras, (b) specifications of the digital camera, (c) conditions of the grid pitch length and grid size [17].

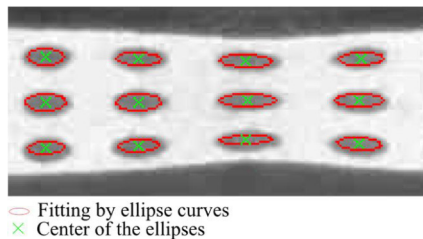


Figure 4. Identified fitting curves and centers of the ellipses of distorted grids [17].

Tensile Test of Spot-Welded Coupon

Tensile tests were performed with JIS No.5 specimen having a spot-welded nugget at the center of the coupon. Figure 5(a) illustrates the shape and geometry of the tensile specimen. The specimen and a tab plate were joined with a spot-welded nugget. Figure 5(b) shows a photograph of the spot-welded specimen fixed in the tensile test machine. The grids for measurement of the strain distribution were printed on the surface of the specimen. Figure 5(c) shows the printed grid around the spot-welded nugget. The grid was printed on the spot-welded specimen. Before grid printing, the surface of nugget was polished with sandpaper to remove the contamination caused by welding. The tensile speed was 2mm/min. During the tensile test, the global strain in the gauge length of 50mm and tensile force were recorded by a digital recorder. Tensile tests of the specimens without spot welding were also carried out with the four high strength steels to investigate the effect of the spot-welded nugget on deformation and fracture behavior, depending on the material strength level. The fracture strain around the nugget and in the base metal was investigated by the strain analysis method in order to discuss the fracture behavior of spot-welded joint in advanced high strength steels.

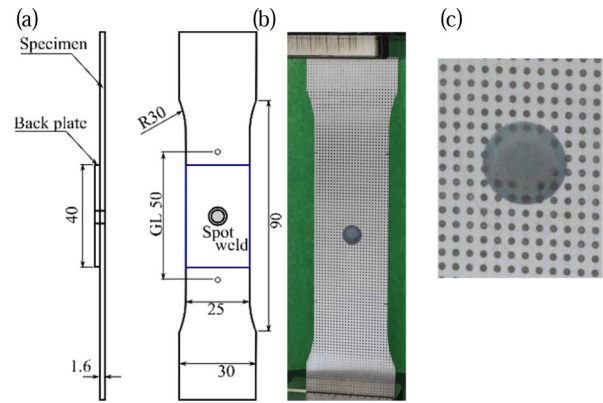


Figure 5. Shape and geometry of tensile test specimen with spot weld. (a) Geometry of spot-weld specimen, (b) photograph of specimen fixed in tensile test machine, (c) printed grids around spot-welded nugget for use in strain analysis.

Three-Point-Bending Test of T-Shape Spot-Welded Specimen

A three-point-bending test method was proposed in this study in order to simulate the fracture around a spot-welded nugget and near the flange edge in crash deformation. The main feature of the method is simultaneous evaluation of spot weld fracture and edge fracture with a simple test specimen and test equipment. Strain measurement during the bending test is also possible by using the strain measurement system shown in Figure 3. Figure 6 shows the dimensions of the specimen, which is called as “T-Shaped spot-welded specimen”. Two L-shaped parts and a top plate are welded at the flange and top portion. The spot pitch in flange area is 30mm. The L-shaped parts are produced by a bending process with the bending radius of 5 mm. The flange edge is shaped by a machining process or a shearing process to investigate the effect of the edge condition on fracture. In the specimens prepared by shearing, the edge surface is not smooth, and includes a burr and fractured surface.

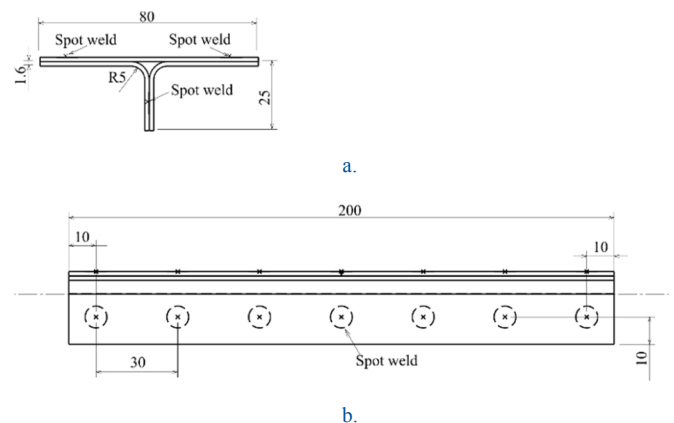


Figure 6. Shape and geometry of T-shaped spot-welded specimen. (a) Section of specimen, (b) location of spot welds in specimen flange.

Figure 7 shows the three-point-bending method. Figure 7(a) shows the dimension of the equipment. The T-shaped spot-welded specimen is supported at the two fulcrums. The fulcrums can be rotated freely