

Development of Fracture Model for Laser Screw Welding

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ABSTRACT

This paper describes the development of a fracture finite element (FE) model for laser screw welding (LSW) and validation of the model with experimental results. LSW was developed and introduced to production vehicles by Toyota Motor Corporation in 2013. LSW offers superb advantages such as increased productivity and short pitch welding. Although the authors had previously developed fracture FE models for conventional resistance spot welding (RSW), a fracture model for LSW has not been developed. To develop this fracture model, many comprehensive experiments were conducted. The results revealed that LSW had twice as many variations in fracture modes compared to RSW. Moreover, fracture mode bifurcations were also found to result from differences in clearance between welded plates. In order to analyze LSW fracture phenomena, detailed FE models using fine hexahedral elements were developed. The analytical results revealed that the fracture modes were determined not only by equivalent plastic strain on the element but also by the stress triaxiality state of the element. The model with new fracture criteria allowed for the fracture mode bifurcation to be recreated in different clearance cases, as observed in the experiments. Based on the above results, a simplified new efficient fracture model for LSW was developed for implementation into large-scale vehicle FE models. The new model consists of hexahedral elements for the nugget part and shell elements for the heat affected zone (HAZ). The new LSW fracture model correlated well with experimental results with respect to fracture mode bifurcation.

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INTRODUCTION

In recent years, safety requirements for vehicles have been increasing due to strengthened safety standards and rating protocols in various countries. As a result, the role of using crash FE analysis for developing vehicles with improved safety performance has been increasing year by year. It is thought that it is important not only to simulate deformation of vehicle structures but also to simulate and evaluate fractures in joints, including RSW [2,9]. The reason is that during the body-in-white (BiW) development stage vehicles consist of several hundred fabricated steel parts, joined by welding, and mainly adopt a monocoque structure. As a consequence of utilizing vehicle body deformation for crash event energy absorption the joints may fracture first in many cases. This is because the joining efficiency rarely exceeds 100% so joints may fracture before the base parts. In particular, it is possible that joint fractures may cause instabilities in crash events due to the bifurcation of joint fracture phenomena. Therefore, to create robust automobile designs, it is important not only to simulate joint fractures but also to evaluate the ratio of loading to fracture criterion (fracture risk).

The authors previously reported on their method for simulating fractures of RSW [1,2,3] and their method of generating the fracture risk [4] by representing RSW with beam elements. Recently, LSW was introduced as a new joining process in which a circular point several mm in diameter is welded between metal plates using a laser beam. This technology is starting to be applied globally to BiW vehicles because of its many advantages such as increased productivity and capability for short pitch welding compared to RSW [5]. However, a LSW model has not been developed even though conventional line laser welding models exist [6].

LSW FRACTURE MODE

To develop a LSW fracture model many comprehensive static experiments were conducted. The fracture modes of LSW were compared to those of RSW. It was revealed that LSW has many additional fracture modes, as described below.

Fracture Mode Variation

Figure 1 shows a schematic drawing comparing the fracture modes observed during RSW and LSW experiment. RSW samples fractured in three modes but LSW samples fractured in six modes.

Fracture Mode	Schematic Drawing	RSW	LSW
(1) Plug Fracture		Available	Available
(2) Interfacial Fracture		Available	Available
(3) Base Plate Fracture		Available	Available
(4) Nugget Fracture (Upper)		Not Available	Available
(5) Nugget Fracture (Middle)		Not Available	Available
(6) Nugget Fracture (Lower)		Not Available	Available

Figure 1. Comparison of fracture modes observed between resistance RSW and LSW samples

The distinctive feature of LSW fracture modes was the variation of complicated fractures through the nugget, as shown in (4) through (6) in Figure 1.

Changes in Fracture Mode and Resistance According to Loading Conditions and Clearance

In the production application of LSW it is very difficult to avoid creating clearance between welded plates (clearance) because, unlike traditional RSW, no clamping force is applied between the plates. For this experiment series, the peel and lap-shear joint specimens shown in Figures 2 and 3 included variations of clearance. The arrows indicate the loading direction. At each end of the specimens retainers were welded for chucking to the experiment apparatus. The outer plates were small and contributed only slightly to the overall force transmission.

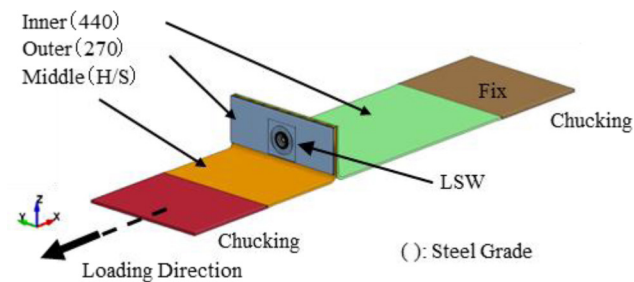


Figure 2. Schematic drawing of a peel specimen

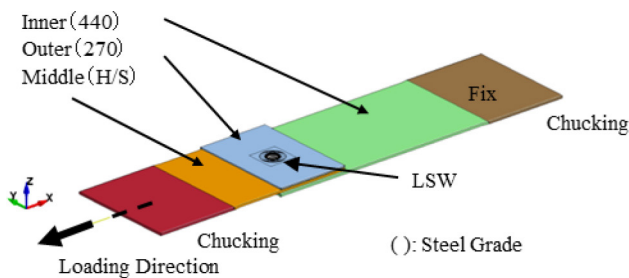


Figure 3. Schematic drawing of a lap shear specimen

The fracture positions observed in this experiment series are indicated by bold red lines in the schematic section drawings of the welded parts shown in Figure 4. The steel tensile strength grades (MPa) are shown to the right of the No.1 specimen drawing. H/S indicates 1500 MPa class hot stamped steel. As can be seen in Figure 4, fracture mode bifurcations were observed in each specimen loading type when the clearance was varied between maximum and minimum.

: Fracture		
Loading	Clearance	Fracture Mode (Schematic)
Peel	Maximum	 Plug Fracture
	Minimum	 Nugget Fracture
Lap Shear	Maximum	 Plug Fracture
	Minimum	 Interfacial Fracture

Figure 4. Comparison of fracture mode bifurcations due to loading and clearance between plates

In the maximum clearance specimens of both loading types LSW underwent plug fractures. In the minimum clearance specimen type the LSW fractured in the nugget part with the peel and lap-shear specimens undergoing a nugget fracture and an interfacial fracture respectively.

Figure 5 shows the fracture resistance results of the peel and lap-shear specimens between maximum and minimum clearance. The fracture resistances of the maximum clearance case were greater than those of the minimum clearance case. This type of relationship, though, has not been observed in RSW.

LSW was shown to have more fracture modes compared to RSW. In addition, it was shown that differences in clearance bifurcated both fracture mode and resistance. Due to these differences, it is thought that LSW will require a more complicated fracture model to simulate its complicated fracture modes and bifurcations.

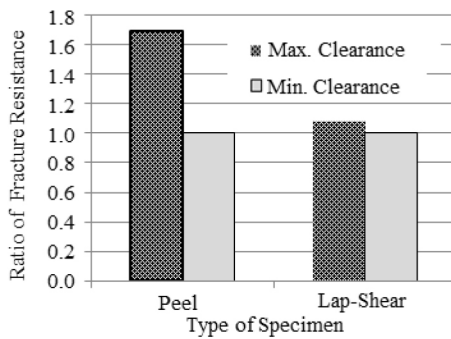


Figure 5. Fracture resistance variation due to loading and clearance between plates in LSW

INVESTIGATION OF THE CAUSES OF LSW'S MULTIPLE FRACTURE MODES

Hardness Distribution

Vickers hardness distributions were investigated to clarify the cause of fracture mode bifurcation. Plates with the combination of thicknesses and material grades, as listed in Table 1, were welded by LSW. The ratios of maximum and minimum hardness in HAZ part to that of the raw material shown in Figure 6. The hardness distribution in the HAZ was found to vary over a wide range.

On the other hand, since there was no material mixing in HAZ part, it was conceivable that speed of cooling after heating by LSW affected mechanical properties of HAZ part. In particular, hardness characteristically increases through quenching in 270 MPa steel and decreases through annealing in H/S material.

The hardness distribution through the nugget part was revealed to be almost uniform. The ratio of the average hardness of the fused materials to that considering the volume fractions of the combination of materials in the nugget part is shown in Figure 6. It was found that for this combination of materials the hardness of the nugget part could be estimated by the average hardness of the fused metal, although the hardness was reduced by about 20% from the average. It was thereby revealed that the hardness of the LSW nugget was affected by all of the materials being fused and mixed and materials with different characteristics were produced by different material combinations.

Table 1. Thickness and steel grade combinations for hardness distribution experiment at nugget and HAZ part

	Thickness	Grade
Plate 1	0.7	270
Plate 2	1.2	H/S
Plate 3	1.2	440

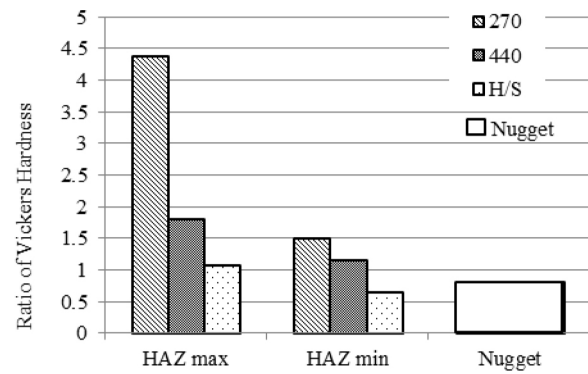


Figure 6. Micro-Vickers hardness distribution in the HAZ and nugget parts of LSW

Development of a Detailed Model of Maximum and Minimum Clearance

A detailed model consisting of 0.03 mm or larger hexahedral elements [7] was developed to investigate the complex fracture mode bifurcation due to differences in clearance between the welded plates. For this model, in order to avoid element formulation difference in the plastic deformation strain calculation only hexahedral elements were used.

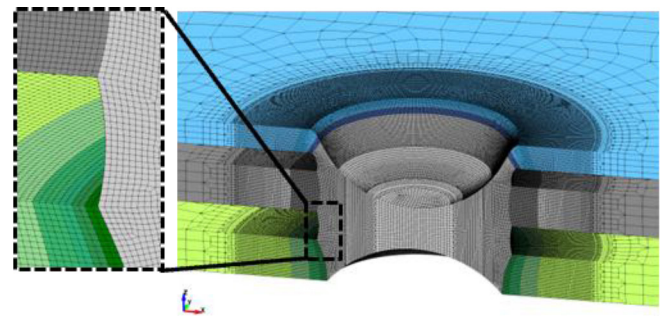


Figure 7. Half of the detailed maximum clearance model developed for LSW to clarify the plate clearance-related fracture mode bifurcation mechanism

The development method was the same as that reported by Kuwahara [4], in which yield stress and tensile strength and so on were assigned to five or six HAZ parts and one nugget part according to the hardness distribution. The centroid section of the detailed model developed is shown in Figure 7. The left part of Figure 7 showed an enlarged breakdown of the nugget where it connects with the plates. Figure 8 shows the assigned definitions of material properties.

Investigation of the Effect of Clearance on Fracture Mode Variation

Figure 9 (a) and (b) indicate the results of the peel experiment for minimum and maximum clearance specimens, respectively. The stroke indicates the cross-head displacement of experimental machine. In both figures, the comparison between the experimental results and the FE analysis using the detailed model were shown. The solid lines indicate the FE results and the dotted lines indicate the experimental results. The physical experiments were repeated three times for each type of specimen.