A Study on Failure of Spot Weld of High Strength Steel

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Abstract: The current paper aims to study the pull-out failure mechanism of spot weld of high-strength material. A FE model was built with solid elements to simulate the corresponding tension test and validated by comparing the load-displacement curves. To validate the model in detail we performed experiments aimed to study the microstructure and micro-Vickers hardness distribution of the spot weld region. The detail FE model of spot weld consists of base sheets, Heat Affected Zone (HAZ) and weld nugget. In the FE simulation study, material failure is modeled with strain-based criterion. The research indicates that failure process includes the deformation of the edge of specimens, axial tension of weld nugget and the deformation in the HAZ. The analysis of stress and strain in FE model shows that notch between weld nugget and HAZ is the stress concentration points, which confirm the phenomenon that pull-out failure of spot weld often takes place at the heat affected zone around the weld nugget.

Keywords: spot weld failure, High Strength Steel, FE simulation, stress strain analysis.

1 Introduction

Spot weld made by resistance welding has been widely used to connect metal sheets of vehicle body since 1950's [1]. Due to the combination of high strength and ductility, dual-phase steels are being actively investigated for future automotive applications [2, 3]. Spot weld failure will greatly influence the vehicle response in crash. Spot weld failure is one of the most common research topic in vehicle design process. Several researchers suggest that there are four separation criterion of spot weld based on force, strain, internal energy and displacement [4, 5, 6, 7]. Considered the influence of four type of loading, Wung [5] developed a force based failure criteria for spot weld design that simplifies the spot weld separation equivalently to the failure of the connection elements. Zuniga and Sheppard [6] attempted to interpret the strength of spot weld using the plastic strain in normal direction of the sheet near the weld nugget as the failure criterion.

Chao, and. Donders S et al. [1, 8] divided spot weld failure into interfacial mode and nugget pullout mode, and found that the failure is in correlation to the material strength, sheet thickness and weld diameter. For the high-strength steels, such as the DP600, hardness of the weld nugget will be the 1.87 ~ 2.45 times higher than that of metal components [3], which enhance the corresponding weld nugget strength greatly. This makes nugget pullout mode more common when high strength steel is used. Such pullout failure of front-beam obtained in component impact test is shown in Figure 1.

For simulation the spot weld failure behavior of pullout mode, Lamouroux and Coutellier [9] and Wang et al. [10] developed the detail models in solid elements and shell elements, respectively. They divided the spot weld area into three zones and in each zone used the different material model. They found that the detail model can improve the simulation of the behavior of pullout failure.

However, few works have been done to analyze the mechanism of failure of pullout mode with detail solid FE model. The goal with the paper is to study the mechanism of failure process by analysis of stress and strain distribution characteristics from FE simulations of spot welding exposed to tension. We used two square-cup specimens jointed by spot weld and exposed it to quasi-static tension test, then used the detail solid finite element model validated by the load-displacement curve from experiments to simulate the spot weld failure process.

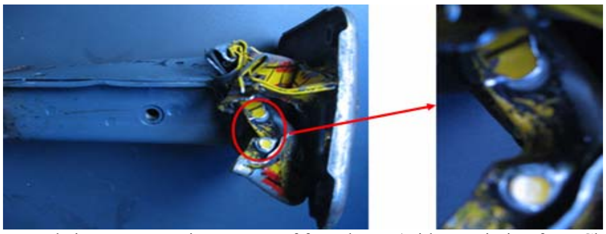


Figure 1. Pullout failure mode in component impact test of front-beam (with permission from Chery Automobile Company).

2 Experimental process

2.1 The design of tension test

According to result of the components impact test of front-beam (Figure 1), pullout failure mode is the most common spot weld failure of the high strength steel. In order to study spot weld failure criteria, researchers had classified spot weld failure tests as single spot weld tensile test include lap-shear tension test, cross-tension test, coach-peel test and KS II test etc, [1, 11]. In the study we performed a series of tension tests of a couple of square-cup specimens in order to evaluate the mechanism of pullout failure. Spot welding condition are summarized in the Table 1, and the dimension of specimen is shown in the Figure 2. We used high strength steel DP600, the sample size was 40 × 40 mm, subjected to quasi-static tensile loading at 2 mm/min (Figure 2). In order to eliminate interference factors in the experiment, three tension test have been carried out under the same conditions. The output from these tests was in form of the load-displacement curves.

Table 1. Welding condition of DP600 metal sheets

Thickness of the sheets [mm]	Weld Time [cycles at 50 Hz]	Hold Time [cycles at 50 Hz]	Diameter of electric tip [mm]	Weld Force [N]	Weld Current [kA]
1.8	14	5	6.4	2250	8.8

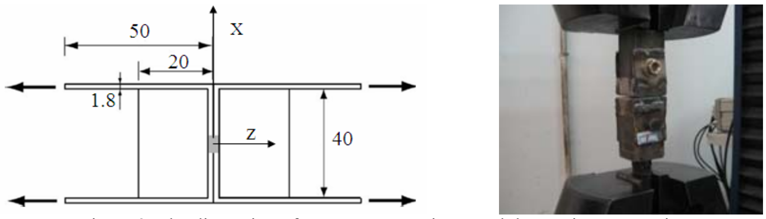
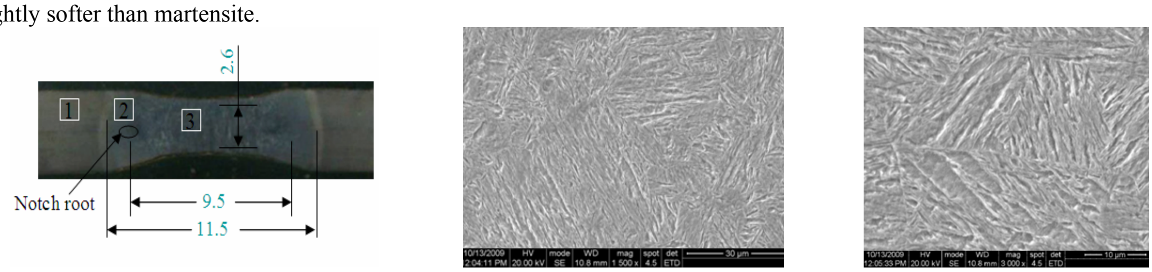


Figure 2. The dimension of square-cup specimen and the tension test equipment.

2.2 Microstructure observation of spot weld region

To get detailed information about the microstructures of spot weld region three additional tests were performed. We separated the specimen from the cross section of spot weld, polished the surface, and then corroded the spot weld region using 4% nitric acid-alcohol. The microstructure in spot weld region is shown in Figure 3. Figure 3a indicates that the microstructure of the metal has been affected by the welding process. It can be seen that spot weld region is divided into three areas with different microstructure. Typical DP600 material mainly consists of martensite (30%) and a-ferrite (area 1). In the area 2, called heat-affected zone, mainly flake martensite and residual austenite can be seen (Fig 3b), because of great cooling rate. In the area 3, called weld nugget, due to smaller cooling rate, equal to an isothermal cooling process, the main microstructures is feathery upper-bainite (Figure 3c), which is slightly softer than martensite.



a. cross section of a spot welded specimen b. microstructure in area 2 (×1500) c. microstructure in area 3 (×3000)

Figure 3. Microstructures in spot-weld area

2.3 Vickers hardness measurement

To further study the influence of welding process on the material property changes in the spot weld area, a procedure of micro-Vickers hardness distribution has been used. This method consists of intending the tested material with a diamond, in form of right pyramid with a square base and an angle of 136º between intender and tested material with the load of 1.96 N. The full load was applied during fifteen seconds. The two diagonals of the indentation left in the surface of the tested material were measured using a microscope and their average calculated. Further the area of the sloping surface of the indentation is calculated. The Vickers hardness [12] is the quotient of the load (in kgf) and the square area of indentation (in μm).

3 Finite element model development and validation

In order to better understand the failure behavior and stress-strain distribution the in our quasi-static tension tests, the author built up a detailed 3D finite element model. The geometry of FE model is based on the dimension of specimens. The microstructure observation of weld region and Vickers hardness measurement indicated that the welding process greatly affected the property in spot weld region. To accurate simulate the spot weld failure, in the model we defined different material properties of the spot weld region divided into: zone with original material properties of DP600, HAZ and weld nugget. The size of weld nugget, refer to GM4488M standard that is the average value of the weld nugget major and minor axis. From Figure 3 we can get weld nugget major axis of 9.5 mm, the short axis of 2.6 mm, so the size of weld nugget is 6.05 mm. Figure 3 shows also that the width of HAZ is about 1 mm. The model did not consider the effect of spot weld indentation. Because the zone with original material properties of DP600 and heat affected zone is the most likely concurrent place of initially fracture, the strain-based failure criteria had been defined for both places as 0.75. Considering the balance of computational cost and model accuracy requirements, the mesh of FE model developed was subdivided in stress concentration regions, and the HAZ and weld nugget areas using the meshing benchmark of 0.3 mm. Boundary conditions in Fe model were the same as these in tension test. The number of total solid elements in the model is 41,170. The computational time-step set at 0.08μs. The model is shown in Figure 4.

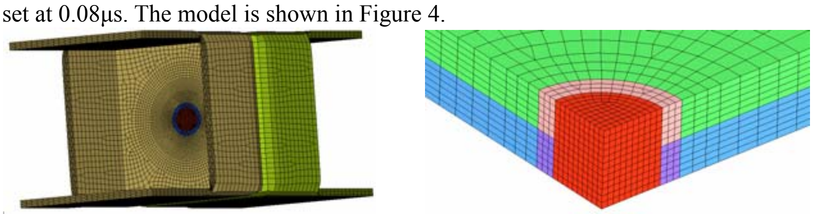


Figure 4. FE model of specimen and element disposition in the nugget and HAZ

3.1 The establishment of three areas of spot welds

3.1.1 Material property of DP600

Based on the standard of GB/T228-2002, the stress-strain curve is shown in Figure 5. Table 2 lists other the material properties of the DP600. In the LS-DYNA software, we used the material model of piecewise linear plasticity to describe properties of DP600 correctly [13].

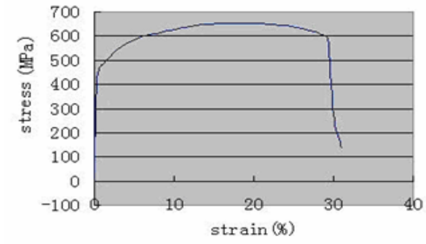


Figure 5. Stress-strain curve for the DP600.

Table 2. Material property of the DP600

material	Density [kg/mm^3]	Young's modulus [GPa]	Poisson's radio	Yield strength [GPa]
DP600	7.8e-6	210	0.3	0.4234

3.1.2 Material property of heat-affected zone and weld nugget zone

Due to the size small size of the HAZ and weld nugget zone, the material properties of these zones are difficult to be obtained through a standard tensile test. Engineers tried to find relationship between the hardness distribution and the yield strength / tensile strength for these zones. Zuniga and Sheppard [14] fount that the distribution of hardness of the material and the yield strength / tensile strength had approximate linear correlation. Lamouroux and Coutellier [8] obtained material properties of the two areas by the method that original properties multiplied by the increase of hardness of HAZ and the weld nugget zone.

In the study we performed measurements of the hardness distribution similar to the way used by Chao [1] that presented a curve of this distribution as shown in Figure 6. His curve shows the existence of three different spot weld regions apparently with different hardness. According to our results the hardness of HAZ and weld nugget is 1.2 and 2.15 times higher than that of original DP600, respectively, It can be seen that this is in agreement to the results presented by Chao [1] therefore we decided to use these values as scaling factor of material properties.

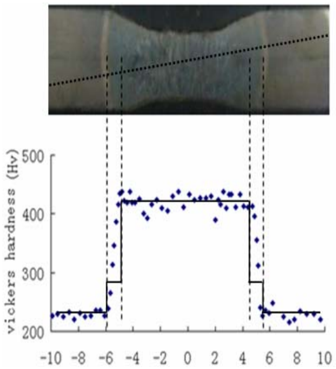


Figure 6. Vickers hardness diagram along spot-weld specimen.

3.2 Model validation

Model validation was done by comparison of the specimen deformation and the load-displacement curve in the process of tension test. Figure 7 shows the specimen deformation in simulation and test after when pull-out failure has occurred. We can see that they have very similar shape of deformation. Moreover, from the comparison of load-displacement curves (Figure 8), it can be seen that the simulation curve basically is in range of three experimental curves, and peak value of tension force and displacement of spot weld failure are similar. These indicate that the solid FE model can simulate the process of the spot weld tension test. The properties of three areas of spot weld are acceptable, and the model is validated correctly.

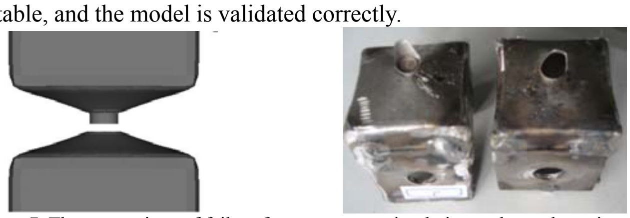


Figure 7. The comparison of failure from computer simulation and tested specimens.

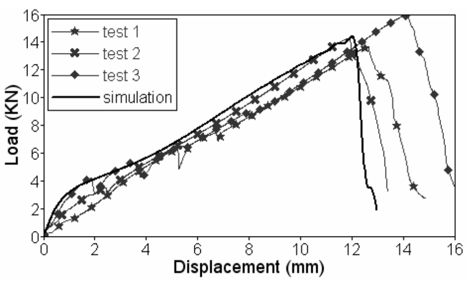


Figure 8. The load-displacement curve from simulation and tests

4 Spot weld Failure Analyses

4.1 Failure process in tension test

Combined the results of spot weld tensile tests of square-cup specimens and these of simulation studies, the spot weld tensile failure process can be divided into four steps, as follow:

1. Bend of the specimens' flange, due to the load applied in the edge of the specimen, generating bending moment;

2. Plastic strain in HAZ, as the load is increasing, the deformation of the specimens is in the form of the plastic elongation. Because of the effect of structural changes, stress is concentrated near the weld nugget, resulting in a larger plastic strain.

3. Just before initial fracture, the stress in HAZ rapidly increases, eventually the plastic strain at the notch root reach the failure criteria, and the initially fracture take place in this point.

4. Fracture propagation. The initial fracture deteriorates the situation of stress concentration; fracture propagates along the normal direction of sheet. Fracture propagates until the weld nugget completely is pulled out from one specimen. The ductile failure mode will not result in sudden drop of the load to zero, because spot welds can withstand a certain load, making the force - displacement curve decreases with a certain degree of slope down to zero value.

4.2 Spot weld failure stress and strain analysis

The impact causing spot weld failure is a complex process. Wung [5] deemed that the spot weld failure is a process of combined tensile, shear loads and moments and torque. In the tension tests in the paper we used a simple load condition model. In such loading condition, most of the initial cracks appear in the stress concentration, so the author analyzed the local stress and strain distribution to study fracture mechanism of spot weld failure.

The stress and strain analysis was made for cross-section of the spot weld specimens. Based on Von Mises yield theory, the effective stress contour of spot-weld area at the time of immediately before initial fracture is shown in Figure 9. Stress concentration can be seen mainly in the junction between HAZ and the weld nugget of the spot weld area; especially in the notch root this stress concentration is critical.

Figure 9. The effective stress contour of spot-weld area at the time of initial fracture

For further analysis of the stress and strain distribution character, considering the symmetry of specimens, the cross section elements in the lower surface of upper specimen we selected the numerical values of these parameters. Figure 10 shows the curves of the shear x and tensile stress of analyzed elements. One can see that tension stress in the points at x = 3 mm and x = -3 in much higher (about two times) than principal stress in x direction, it means that the tested material will be damaged due to tension stress concentration in the notch roots. The strain distribution figure also displays the same phenomenon (Figure 11). The figure shows clearly that the tension strain is dominating. These indicate that the main factor of pull-out failure mode in square-cup specimens is tension stress and strain, and the notch root is the vulnerable point of initial fracture.

In the process of tension test, as the displacement increased, the angle between the plates of spot weld becomes larger. This also deteriorates the situation of stress concentration in the notch roots, then the strain value in these points reach the strain-based criteria, and generate the initially fracture. Eventually fracture propagates until the weld nugget was pulled out completely from one specimen.

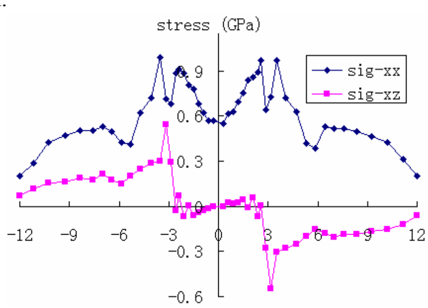


Figure 10. The stress distribution in the spot-weld area at the time of initial fracture

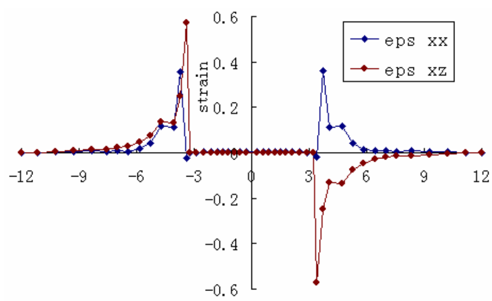


Figure 11. The strain distribution in the spot-weld at the time of initial fracture

5 Conclusions

In order to study the failure mechanism of pullout mode of the spot welds by mathematical simulation, following a pull-out laboratory tests, the authors used a finite element model constructed with solid elements. The result of the observation of microstructure and Vickers hardness measurement in separate tests confirmed that the detail model is necessary. Such model includes spot weld region divided into three zones with different material properties: zone with original material properties of DP600, HAZ and weld nugget zones. We also could overcome the shortcoming of use solid elements in the computation of FE model through the local grid refinement and use strain-based failure criteria. The model has been validated by regarding the failure deformation and load-displacement curves.

Analysis of pull-out failure of the spot weld area showed that the process can be divided into four phases: bending of the specimens flange, plastic strain in HAZ, initially fracture and fracture propagation until disconnection of the spot weld. The analysis of the local stress and strain distribution indicates that the failure of spot weld is mainly affected by the tension force in X direction. Due to the structure and material change in notch root, it is most likely that the initial fracture will occurs in this place. Our study could explain the phenomena that pull-out failure of spot welds mainly occurs around the heat-affected zone. This is mainly coursed by the concentration of tension stress around the weld nugget and not only due to high shear stress.

Acknowledgment

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