Improved simulation method of automotive spot weld failure with an account of the mechanical properties of spot welds

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Abstract: In this paper, the microstructure and mechanical properties of spot weld were studied, the hardness of nugget and heat affected zone (HAZ) were also tested by metallographic microscope and microhardness tester. The strength of the spot weld with the different parts' area has been characterized. According to the experiments result, CAE model of spot weld with HAZ structure was established, and simulation results of different lap-shear CAE models were analyzed. The results show that the spot weld model which contained the HAZ has good performance and more suitable for engineering application in spot weld simulation.

1. Introduction

With the development of body connection technology, various connection methods have been applied in car bodies design, including resistance spot welding, laser welding, riveting, adhesive bonding and so on. Resistance spot welding is still the main method to assemble sheet metal part/panels for automotive bodies. The modern frameless body is the combination of metal/composite and joints, a car body contains thousands of spot welds, which occupies more than 75% of the car body assembly work [1].

According to crash experiment result, failure of spot welds has the critical influence on crash analysis [2] and is the main concern during safety design of automobiles. To improve the accuracy, reliability, and efficiency of joint failure simulation, spot welds are simplified to beam or solid elements as shown in figure 1, and failure criteria are applied in the elements according to different load conditions. Traditionally, layers of shell elements are welded by beam element through a single node, which is not able to transfer torque [3] and lead to the deviation between simulation and experimental result. While the solid weld elements connect layers through multiple modes, they are able to simulate the stress and torque at the same time. Studies of simulation methods with solid weld element were carried out by relevant researchers. Scie et al [4] analyzed a cluster of solid hexahedral elements from 1-Hex to a 16-Hex, respectively, and found that beam and single hex element spot welds should not be treated as mesh-independent in terms of internal forces and displacements. Wu [5] found that solid elements with complete integral shell elements had a better performance in the crash simulations.

However, a simple spot weld model failed to considered different mechanical properties of different spot weld parts, which led to inaccurate failure simulation results. Moreover, it failed to meet the stringent requirements on the accuracy for crash simulation.

In this paper, micromechanical and macro-mechanical properties of spot weld between B340-590DP and B340LA steel were tested. Based on the test results, the CAE model of spot weld was applied, and the comparison was made between testing and simulation result. The results show that the new developing spot weld modeling method was more accurate and suitable for engineering application.
Figure 1. Simulation of spot weld using beam element (a) and solid elements (b)

2. Experimental equipment and methods

In the experiment, dual-phase steel B340-590DP and low alloy steel B340LA steel sheets (thickness of 2mm) were produced by Baosteel. The lap-shear spot weld specimens were made by resistance welding machine as shown in figure 2. Lap-shear specimens were tested with WDW100 universal material testing machine with the tensile speed of 2mm/min. The metallographic structure was observed by Leica optical metallurgical microscopy, micro-hardness of the spot weld was also measured by Vickers Indenter under the load of 100gf. The CAE model based on the experimental results was realized via LS-DYNA software package.

Figure 2. Resistance welding machine (a) and lap-shear spot weld specimen (b)

3. Analysis of the mechanical properties

3.1. Metallographic structure

Figure 3 shows the cross-section of the B340-590DP/B340LA spot-weld. According to the microstructure character of the spot weld, it can be subdivided into three different regions: nugget, heat affected zone (HAZ), and base metal (BM). There is also a significant boundary between BM and HAZ. As it is shown in metallographic (figure 3), BM of B340LA is made of ferrite and pearlite predominantly. It is due to the high temperature during the welding process, The HAZ of B340LA transforms into ferrite and bainite. For B340-590DP type, the BM consists both ferrite and martensite. The contents of martensite increase significantly near the HAZ part. Nugget is the metallurgical combination of two layers’ metal sheet, and its microstructure is also martensitic.
3.2. Microhardness analysis
The microstructure of spot weld is different, so it leads to different mechanical and failure performance among BM, HAZ, and nugget. Microhardness of different part weld joints is shown in figure 4. The nugget diameter is 7 mm and the distance between neighboring measure points is 200um approximately. Microhardness of B340-590DP and B340LA base metal is 225Hv and 180Hv respectively, the average value in nugget is 425Hv. The results show that the various spot weld parts have different mechanical properties due to varying metallographic structure characteristics.

3.3. Transformation of tensile strength and microhardness
In order to analyze the difference between the material microstructure of weld area, the microhardness was converted to the tensile strength value, which could be used in calculations via the CAE model.

The relationship between tensile strength and hardness of steel is described by the international standard ISO 18265:2003 and ASTM E140-12be1 [6, 7], which can be seen from the research result of Shen [8]. The tensile strength has a linear relationship with hardness value for mild steel and alloy steel. According to the above analysis, the mechanical properties of B340-590DP and B340LA steels are shown in table 1.

The tensile strength of nugget and HAZ, which cannot be measured directly, may be also calculated by the above method. The relationship between the tensile strength and hardness of B340-590DP and B340LA is shown in figure 5.
Table 1. Mechanical properties of B340-590DP and B340LA steels

|                | Tensile strength, MPa | Young’s modulus, GPa | Microhardness (HV0.1) |
|----------------|-----------------------|----------------------|-----------------------|
| B340-590DP     | 598                   | 203                  | 225                   |
| B340LA         | 421                   | 206                  | 181                   |

Figure 5. Relationship between tensile strength and microhardness

The relationship between tensile strength and microhardness can be described as follows:

\[ \sigma = 4.02x - 307.1 \]  

where \( \sigma \) is tensile strength, and \( x \) is microhardness of steel.

The tensile strength of HAZ and nugget of the spot weld is calculated by equation (1) and shown in table 2 below.

Table 2. Tensile strengths of HAZ and nugget

|                | Microhardness (HV0.1) | Tensile strength, MPa |
|----------------|-----------------------|-----------------------|
| HAZ_{B340-590DP} | 309                   | 935.1                 |
| HAZ_{B340LA}    | 295                   | 878.8                 |
| nugget          | 425                   | 1401.4                |

4. Lap-shear test and FEM analysis

4.1. Modeling approach of spot weld

According to the previous research, the solid elements have better performance than beam elements in spot weld simulation, so the simple solid element was established in a lap-shear model (Figure 6b). In order to obtain more accurate results, the HAZ part was included in the spot weld model, which was established in the lap-shear model (Figure 6c). The thickness of shell elements was defined as 2mm, the bottom of the specimen was constrained, while the top of the specimen was subjected to tensile load with the displacement rate of 2mm/min. The size of nugget and HAZ were both consistent with the results of measurement. The HAZ part was defined as a layer of the washer.
Material parameters of HAZ and nugget were derived from the tensile strength of base metals in table 2, while true stress-strain curves for the input into the material map “MAT_24 piecewise_linear_plasticity” are depicted in Figure 7.

4.2. Test and simulation results
Figure 8 shows the test and simulation results of solid elements with and without the HAZ part. It can be seen that the failure occurred in B340LA base metal, which had the lowest strength. Both models have good performance in predicting the original failure position, but the failure crack propagation of two models diverged from each other. For the simple element model simulation, the crack extended path was surrounding the nugget. Finally, the base metal peeled off from the nugget. The calculation results via the model containing the HAZ part show that the crack initiation occurred in the base metal near the HAZ part, while crack propagation took place in the perpendicular direction to the tensile axial load, as it was observed in the test.
Figure 8. Failure modes in the test (a) and via CAE models with simple solid elements (b) and solid elements with HAZ (c).

Figure 9 shows the load-displacement curves of lap-shear test and simulation. It could be seen that at the beginning of the curve, tensile force was increase linearly due to the elastic deformation of the base metal. During the deformation process, the sheet of B340LA base metal around the nugget started to warp, and the flat curve is shown accordingly. Cracks followed the deformation and load decreased significantly until the specimen was failed completely.

By comparing the results of two simulation methods, it can be found that both models matched well with test curve in the stage of elastic deformation, regardless of the HAZ part, but the result of simple solid element model had errors in peak load value and failure displacement because of quick deleting of grids around the nuggets, correspond to the previous failure process of simple model. As for the result of solid element model with HAZ, the growth of the failure crack continued for a long period, which led to a long-term loading, so the solid element spot weld simulation model with HAZ part yielded the identical results to the experimental data.

5. Conclusions

- The hardness in the nugget and HAZ is significantly higher than the base metals of B340-590DP and B340LA due to the different metallographic structure.

- Based on the microstructure of spot weld, this paper established a simulation model which solid element of nugget and HAZ part is included. The test comparison of lap-shear test and two kinds of simulation models indicated that the model with HAZ has better performance in failure analysis, and more suitable for engineering applications.
Figure 9. Load-displacement curves of test and simulation

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