Research Article

Influence of Tensile Speeds on the Failure Loads of the DP590 Spot Weld under Various Combined Loading Conditions

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This paper is concerned with the evaluation of the dynamic failure load of the spot weld under combined axial and shear loading conditions. The testing fixture is designed to impose the combined axial and shear load on the spot weld. Using the proposed testing fixtures and specimens, quasi-static and dynamic failure tests of the spot weld are conducted with seven different combined loading conditions. The failure load and failure behavior of the spot weld are investigated with different loading conditions. Effect of tensile speeds on the failure load of the spot weld, which is critical for structural crashworthiness, is also examined based on the experimental data. The failure loads measured from the experiment are decomposed into the two components along the axial and shear directions and failure contours are plotted with different loading speeds. Dynamic sensitivities of failure loads with various combined loading conditions were also analyzed. Experimental results indicate that the failure contour is expanded with increasing loading speeds and failure loads show similar dynamic sensitivity with respect to the loading angles.

1. Introduction

Increasing concern of environmental safety and reduction of fuel consumption motivates car manufacturers to use lightweight materials having a higher tensile strength coupled with better ductility. By reducing the weight of a car less fuel consumption along with less CO₂ emission can be achieved. Considering the safety standards required in the automobile industry, dual phase (DP) steel has gained its popularity as this steel has a higher tensile strength in conjunction with higher elongation compared to the steel grades of similar yield strength [1]. The resistance spot welding process has become indispensable in the joining of sheet metals in the automobile industry since the 1950s. Because a modern vehicle typically contains several thousand spot welds, it is extremely important to understand the strength of the spot weld under quasi-static, fatigue, and impact loading conditions in order to evaluate durability and crashworthiness of an auto-body [2]. Failure of a spot weld is likely to occur

prior to failure of the base metal when a large load is applied to the structure since extremely high stress is concentrated at the interface between the nugget and the base metal [3]. It is necessary to estimate the strength of spot welds of DP steel sheets in order to provide a failure criterion of a spot weld in the structural analysis or crashworthiness assessment of auto-body members. For that purpose, lap-shear tests, coach-peel tests, and cross-tension tests have been elaborately performed to estimate the failure loads of the spot weld [4–6]. It is, however, insufficient to perform simple lap-shear tests and cross-tension tests to construct the failure criteria that describe the behavior of spot welds under combined loading conditions because spot welds in automotive components are subjected to complicated loading conditions when they undergo deformation.

With advances in computer simulation technology, automotive companies attempt to implement accurate spot weld models into finite element analysis so as to predict the failure of spot-welded components in the crash analysis of

FIGURE 1: Fixture set with pin-joints for failure tests of a spot weld under combined loading conditions: (a) schematic diagram of a fixture; (b) fabricated testing fixtures at various loading angles.

FIGURE 2: Design of specimen to impose the constant ratio of axial and shear loads on the spot weld during tests: schematic description of a specimen with a guide plate; (b) loading path acting on the spot weld at various loading angles (FEM results).

an auto-body. In order to describe the failure of a spot weld in the crash analysis, it is necessary to evaluate the failure characteristics of a spot weld under impact loading condition. Birch and Alves [7] conducted dynamic lap-shear tests of spot-welded mild steels using a servohydraulic testing machine. Schneider and Jones [8] performed dynamic coach-peel tests at a crosshead speed of 0.8 m/s. Bayraktar et al. [9]

investigated dynamic failure loads of spot-welded lap-shear specimens using a Charpy impact test. Their experimental results revealed that the dynamic failure load of spot welds increases relative to the quasi-static failure load. Sun and Khaleel [10] also observed the strain-rate dependent failure load of spot welds in dynamic cross-tension tests. Khan et al. conducted drop weight test using lab-shear specimen to

FIGURE 3: Decomposition of the applied load on a spot weld into the axial and the shear component at the loading angle of ϕ .

investigate the impact performance of spot welds in advanced high strength steels [11]. It is, however, not feasible to perform dynamic lap-shear, cross-tension, and coach-peel tests for constructing a strain-rate dependent failure criterion that describes the behavior of spot welds under impact loading conditions because spot welds in automotive components are subjected to complicated dynamic loading conditions when they undergo crashed deformation [12].

In this paper, the failure behavior of the DP590 spot weld under combined loading conditions is investigated under quasi-static and impact loading condition. Dynamic failure tests of the spot weld are conducted with seven different combined loading conditions at various tensile speeds from quasi-static to 1.2 m/s. Dynamic effects on the failure load of the spot weld, which is critical for structural crashworthiness, are examined based on the experimental data.

2. Dynamic Failure Tests of a Spot Weld under Combined Loading Conditions

2.1. Testing Fixtures to Impose Combined Loading Conditions on the Spot Weld. In order to impose the combined axial and shear loads on a spot weld, specially designed testing fixtures and specimens were adopted in this paper [13]. The testing fixture shown in Figure 1 contains the pin-joints that eliminate the horizontal force and bending moment. The specimen shown in Figure 2(a) involves guide plates that prevent unfavorable rotation of the nugget due to bending deformation. The testing fixture and specimen ensure a combined loading condition with a constant ratio of the shear load to the axial load during the test, as shown in Figure 2(b) [13]. Therefore, as explained in Figure 3, the applied load F_z can be decomposed into the axial load F_N and the shear

load F_S at the nugget region using the simple trigonometric functions:

$$\begin{aligned} F_N &= F_z \cos \phi \\ F_S &= F_z \sin \phi. \end{aligned} \quad (1)$$

Here, F_N , F_S , and ϕ denote the axial load, the shear load, and the initial inclined angle with respect to the pulling direction, respectively. The inclined angle ϕ is equal to the loading angle, which represents the angle between the load application line and the centerline of the specimen.

2.2. Testing Material and Preparation of Specimen. The spot weld of DP590 with the thickness of 1.0 mm is considered in this paper. The chemical compositions are listed in Table 1. Prior to spot welding of a specimen, the specimen surface was wiped with a weak acetone solution using a cloth in order to remove grease and dirt from its surface. Spot welding was then performed using a static spot/projection welding machine. The welding schedules shown in Table 2 were determined after several trials with the aid of industry standards to guarantee a button-type failure.

The specimen used in the tests is shown in Figure 4(a). To restrict the bending of the region outside the spot weld, two guide plates made of SPFC590 steel with the thickness of 3.2 mm were attached onto the outsides of the specimen in the following procedure.

- (1) Two guide plates with a hole at the center are prepared. Thickness and hole diameter of the guide plate are 3.2 mm and 10 mm, respectively.
- (2) A guide plate was joined with a steel sheet on one side using six points of spot welding around the hole at the center of the guide plate.
- (3) Two pairs of the joined guide plate and the steel sheet were spot welded to each other through the holes at the center of guide plates.

As the diameter of the hole in the guide plate was 10 mm, the six spot weld points that joined the guide plate and the steel sheet only serve to prevent excessive bending of the spot-welded region; they have little influence on the strength of the spot-welded region in the specimen. Additionally, a pure shear test was also performed in order to obtain the failure load at a loading angle of 90° . Three sheets are joined with a spot weld so that only the shear load is applied on the spot weld as shown in Figure 4(b). Cross-sectional shape and hardness profile of the specimen are also depicted in Figure 5.

2.3. Testing Equipment and Conditions. In the present experiment, the servohydraulic high speed material testing machine [14] shown in Figure 6 was utilized in order to obtain the dynamic failure loads of the spot weld at intermediate strain rates. The machine has a maximum stroke velocity of 7800 mm/s, a maximum load of 30 kN, and a maximum displacement of 300 mm. For the dynamic failure test, the instrument that measures the load and the displacement must have good response in the dynamic motion since failure tests

FIGURE 4: Specimens used in the failure test: (a) combined loading tests at loading angles of 0°, 15°, 30°, 45°, 60°, and 75°; (b) pure shear tests at loading angle of 90°.

FIGURE 5: Cross-sectional shape and hardness profile of the specimen.

FIGURE 6: High speed material testing machine.

TABLE 1: Chemical composition of steel sheets tested.

Material	Chemical composition [wt%]						
	C	Si	Mn	P	S	Al	Fe
DP590 (thickness: 1.0 mm)	0.073	0.034	1.75	0.075	0.005	0.038	Bal.

TABLE 2: Welding schedule and associated nugget diameter of DP590.

Material	Squeeze time (cycles)	Weld time (cycles)	Hold time (cycles)	Weld current (kA)	Weld force (kN)	Nugget diameter (mm)
DP590 (thickness: 1.0 mm)	20	15	20	7.8	3.5	6.32

TABLE 3: Dynamic failure loads of a spot weld for DP590 at various loading angles.

Loading angle (°)	Failure Load of a spot weld for DP590 1.0t (kN)											
	Quasi-static 1×10^{-5} m/s						Dynamic					
				0.01 m/s			0.1 m/s			1.2 m/s		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
0°	9.20	9.08	9.29	9.72	9.80	9.63	10.02	9.94	10.08	10.36	10.29	10.21
15°	8.47	8.38	8.61	8.81	8.08	8.94	9.23	9.16	9.35	9.43	9.58	9.69
30°	8.10	8.22	8.34	8.89	8.77	8.73	8.85	9.06	8.98	9.29	9.23	9.36
45°	8.57	8.55	8.73	9.13	9.18	9.26	9.39	9.48	9.43	9.68	9.79	9.56
60°	10.09	9.88	10.13	10.48	10.76	10.63	10.74	10.86	10.92	11.12	11.38	11.23
75°	12.66	12.42	12.47	13.16	13.08	13.23	13.59	13.47	13.76	14.18	13.92	14.03
90°	16.88	17.15	16.92	17.91	18.02	17.68	18.28	18.62	18.45	19.01	18.74	18.89

at intermediate strain rates last only for several milliseconds. The machine equipment is set up with a piezoelectric load cell of Kistler 9051A. The displacement is acquired by a linear displacement transducer (LDT) from Sentech Company. The testing fixtures were mounted in the high speed material testing machine as shown in Figure 6. Dynamic failure tests at the different tensile speeds of 1×10^{-5} m/s, 0.01 m/s, 0.1 m/s, and 1.2 m/s were conducted under seven different loading conditions until the spot weld failed and the specimen separated into two components. The load and displacement were measured simultaneously during each test. The load was measured using the load cell in the testing machine and the displacement was calculated from the relative movement of the two pull bars.

3. Evaluation of Dynamic Effect on the Failure Load of a Spot Weld

3.1. Failure Loads with Various Loading Angles and Loading Speeds. With the testing conditions described in Section 2.3, dynamic failure tests were carried out at seven different loading angles to evaluate the dynamic impact failure load of the spot-welded specimen. Figure 7 shows load-displacement curves for spot-welded DP590 specimens at various loading angles with different tensile speeds of 1×10^{-5} m/s, 0.01 m/s, 0.1 m/s, and 1.2 m/s. The figure shows that the maximum load decreases as the loading angle increases when the loading angle is less than 30°, whereas the maximum load increases as the loading angle increases at the interval from 45° to 90°. Figure 8 shows the typical load-displacement curves for spot-welded DP590 specimens at the loading angles of 0°, 45°, and 90° with different loading speeds. The figure shows that the maximum load for spot welds in DP590 steels increases when the imposed strain rate increases. When the tensile speeds change from 1×10^{-5} m/s, which is almost

quasi-static states, to 1.2 m/s, the maximum load for spot-welded DP590 increases by approximately 13%. Failure loads obtained from tests for spot-welded DP590 specimens at various loading angles and strain rates were listed in Table 3. Figure 9 represents the deformed shapes of the specimens made of DP590 at the onset of failure at various loading angles with the tensile speed of 1.2 m/s. Shear failure mode was observed around the circumferential boundary of the nugget as shown in Figure 9, when the pure axial load acts on the spot weld at the loading angle of 0°. For combined axial and shear loading conditions, failure is initiated with the localized necking in the interface between the HAZ and the base metal. A similar failure mechanism was also observed in the quasi-static experimental results [13, 15].

3.2. Dynamic Sensitivity of the Failure Load and Failure Contours. Failure contours of a spot weld at different tensile speeds were also constructed by decomposing the failure loads measured in the experiment into two components along the axial and shear directions. These were plotted in the force domain as shown in Figure 10, which shows that the failure contour expands as the tensile speed increases. In order to examine the effect of the tensile speeds on the failure load of spot welds, the axial and shear failure loads were plotted in a logarithmic scale of the tensile speeds as shown in Figure 11. The figure shows that the axial and shear failure load increase as the tensile speeds increase. Moreover, the dynamic sensitivity can be interpolated in terms of the quasi-static failure load and the logarithm of the tensile speeds. Dynamic sensitivity of the failure loads at various loading angles was also investigated. The dynamic failure loads at various loading angles were normalized by the quasi-static loads as $\bar{F}(v) = F(v)/F_0(v_0)$, where $F_0(v_0)$ denotes the quasi-static failure load at a given loading angle. The normalized failure loads of spot-welded DP590 specimens were plotted in

FIGURE 7: Load-displacement curves of spot-welded specimens for DP590 at various loading speeds: (a) quasi-static (1×10^{-5} m/s); (b) dynamic (0.01 m/s); (c) dynamic (0.1 m/s); (d) dynamic (1.2 m/s).

Figure 12 at various loading angles. The figure shows that the tensile speeds have effects on the normalized failure loads for a given loading angle while the normalized failure loads at a given tensile speed are insensitive to the loading angles, which implies that the failure loads show similar dynamic sensitivity with respect to the loading angles.

4. Conclusion

In this paper, effects of tensile speeds on the failure load of a DP590 spot weld are evaluated under combined axial and shear loading conditions. Dynamic failure tests of spot welds were conducted at seven different combined loading conditions in order to obtain the dynamic failure loads of spot welds at the tensile speed from quasi-static to 1.2 m/s. The experimental results indicated that the failure load decreases as the loading angle increases when the loading angle is less than 30° , whereas the failure load increases as the loading

FIGURE 8: Load-displacement curves of spot-welded specimens for DP590 at various loading angles: (a) 0°; (b) 45°; (c) 90°.

FIGURE 9: Deformed shape of the specimen made of DP590 spot welds at various loading angles with the tensile speed of 1.2 m/s.

FIGURE 10: Dynamic failure contour of the DP590 spot weld with various tensile speeds.

FIGURE 11: Dynamic sensitivity of failure loads of DP590 spot weld: (a) axial failure load; (b) shear failure load.

FIGURE 12: Normalized failure loads of a DP590 spot weld at various loading angles.

angle increases at the interval from 45° to 90°. Failure contours of a spot weld at different tensile speeds were also constructed by decomposing the failure loads measured in the experiment into two components along the axial and shear directions. The constructed failure contours indicate that failure contour expands as the tensile speed increases. The results also revealed that dynamic sensitivity can be interpolated in terms of the quasi-static failure load and the logarithm of the tensile speeds. Moreover, the failure loads show similar dynamic sensitivity with respect to the loading angles.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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