Mechanical Performance of Resistance Spot Welded Steel Sheets

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Abstract. Mechanical performance of resistance spot welded steel sheets was evaluated under quasi-static and dynamic loading conditions. Numerical inverse calibration method was mainly utilized to characterize mechanical properties especially for flow curves and ductile fracture criteria of constituent zones of the welded joints. For the base sheets, standard tensile test and high-speed tensile test was conducted under quasi-static and dynamic loading conditions, respectively. Mechanical properties of the weld zones were characterized using the developed miniature tensile specimen. Implementing the mechanical properties and structure to the finite element model, finite element simulation was used to evaluate the mechanical performance of two distinct weld coupons.

1. Introduction

Advanced high strength steel (AHSS) sheets have been increasingly applied to reduce weight of an automotive body while compromising crash performance for passenger safety. Despite development of various welding technologies, resistance spot welding (RSW) is still an economical and effective way to integrate parts into a full body.

Mechanical behaviour of the spot welded structure determines mechanical performance of the integrated body such as structural rigidity and crashworthiness. Especially, the failure characteristics of a spot welded joint should be evaluated for more accurate analyses of the energy absorption potential. There have been substantial efforts to investigate failure performance of a welded joint. Chao [1] experimentally measured failure strength and failure modes of welded coupons. The lower bound limit load analysis was also performed by Lin et al. [2] to unveil the correlation between failure strength and such geometric parameters as sheet thickness, nugget diameter, etc. A numerical approach [3] was also executed to predict the maximum load of welded coupons. However, the findings on the previous researches cannot take account of general failure phenomena involving interfacial and pull-out modes.

The main objective of the present study is to evaluate mechanical performance of the spot welded joints of AHSS sheets under quasi-static and dynamic loading conditions. Specimens of the special shape [4, 5] was subjected to tensile loading for material characterization of the weld nugget. Implementing the mechanical properties and structure to the finite element (FE) model, finite element simulation was used to evaluate the mechanical performance of two distinct weld coupons, especially...
for failure characteristics. The spot welded joints were fabricated with the transformation induced plasticity steel (TRIP) sheet whose thickness and grade are 1.2 mm and 980 MPa, respectively.

2. Material characterization
Mechanical properties of TRIP were measured by performing the standard tensile test procedure suggested by ASTM E 8M. Isotropy of the base sheet was assumed because directional test showed little difference between each other. The measured properties of the base sheet are summarized in table 1.

| E [GPa] | YS [MPa] | UTS [MPa] | Parameters for Swift hardening | Strain rate-sensitivity, m |
|---------|----------|-----------|------------------------------|--------------------------|
| 205.3   | 767.3    | 999.0     | 1482                         | 1.680E-03                |

Strain rate-sensitivity of hardening for the base sheet was also obtained by conducting the tensile test with a set of strain rates ranging from 0.001 to 100.0 /s. In an average sense, the rate-sensitivity, \( m \), was fitted to the following equation (1) and its value is listed in table 1.

\[
\bar{\sigma} = \sigma_0 \left( \dot{\varepsilon} / \dot{\varepsilon}_0 \right)^m
\]

In the equation (1), \( \sigma_0 \) denotes flow stress curve at the reference strain rate of \( \dot{\varepsilon}_0 \) and strain rate of 0.001 /s was employed as the reference rate. In addition, hardening behaviour beyond the UTS point was inversely characterized by FE analysis in order to accounting for the hardening deterioration after UTS as micro-voids evolve to form macro-crack [4]. Simultaneously, fracture criterion was inversely determined. The characterized hardening and fracture criterion are depicted in figure 1.

![Figure 1](image-url)

**Figure 1.** Comparison of (a) the hardening curves and (b) the fracture criteria between the base sheet and its weld nugget.

As for the weld nugget, the miniature specimen, devised by the present authors [4, 5], was subjected to tensile loading and numerical inverse analysis was conducted to extract mechanical properties of the weld nugget from the measured load-displacement curve. Figure 2 shows the miniature specimen designed to induce major deformation on the weld nugget region by its specific geometries. For better accuracy of simulation, the FE model considered the geometric features of the welded joint such as nugget diameter, dent size, and gap based on the optical microscopic observation as shown in figure 3.
The FE simulation of the miniature tensile test was iteratively conducted until the simulated load-displacement curve well matched with the experiment one. The resulting hardening behaviour and fracture criteria of the weld nugget are depicted in figure 1 with comparison of the base sheet.

3. Mechanical performance of spot welded joints

Various types of single welded coupons were used to evaluate the mechanical performance of the spot welded joint. Lap-shear (LS) and U-shape (US) tension tests were conducted under a quasi-static loading condition, while LS and coach-peel (CP) tests under a dynamic loading condition. Interfacial failure mode was observed in all the coupon tests except for the US test under a quasi-static loading, as shown in figure 4.

Figure 2. Shape of the miniature specimen.

Figure 3. Metallographic observation of the welded joint.

Figure 4. Force–displacement curves and failure modes; (a) and (b) for LS and US tension tests under a static loading condition, (c) and (d) for LS and CP tension tests under a dynamic loading condition.
Interfacial failure mode has not been considered and predictable in the previous research because earlier findings showed that well fabricated welded joints especially for the conventional steels usually induces pull-out failure mode. The FE model developed in this research turned out to be capable of evaluating failure characteristics in general. Implementing the characterized properties especially for the weld nugget, finite element analysis simultaneously reproduces failure strength and failure mode for LS and CP tests under a dynamic loading condition as well as for LS and US tests under a static loading condition, as shown in figure 4.

4. Conclusions
Mechanical performance of resistance spot welded steel sheets was evaluated under quasi-static and dynamic loading conditions. Numerical inverse calibration method was mainly used to characterize the mechanical properties especially for flow curves and ductile fracture criteria of constituent zones of the welded joints. The standard and the miniature tensile tests were carried out for inverse characterization of the base sheet and the weld nugget, respectively. Implementing the mechanical properties and the geometric features to the finite element model, failure characteristics of spot welded coupons were successfully evaluated by simulation. In a consequence, the FE model developed in this research proves to have potential use for evaluation of failure in a spot welded structure.

References
[1] Chao Y J 2003 Sci. Technol. Weld. Join. 8 133.
[2] Lin S H, Pan J, Wu S R, Tyan T and Wung P 2002 Int. J. Solids Struct. 39 19.
[3] Yang X, Xia Y and Zhou Q 2010 Eng. Fract. Mech. 77 1224.
[4] Chung K, Noh W, Yang X, Han H N and Lee M G 2017 Int. J. Plast. 94 122.
[5] Noh W, Kim W, Yang X, Kang M, Lee M G and Chung K 2017 Int. J. Mech. Sci. 121 76.