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# Simple and effective failure analysis of dissimilar resistance spot welded advanced high strength steel sheets

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ABSTRACT

The failure of welded structures was analyzed considering dissimilar combinations of advanced high strength steels (AHSS) and a conventional mild steel. A method to characterize the mechanical properties of hardening behavior along with the deterioration associated with micro-void development and fracture criterion based on a modified damage model was applied by employing simple but effective experimental and numerical inverse procedure. The proposed procedure was solely based on standard and miniature simple tension tests for base sheets and weld nuggets, respectively. The identified plastic and failure properties were applied to the analysis of the failure mode and strength in the two well-accepted coupon tests of lap-shear and U-shape tension tests for DP980-TRIP980 and GMW2-TRIP980 dissimilar welded sheets. The analysis confirmed that the distinct failure behavior in the coupon tests for the two dissimilar weld cases was mainly due to the competition between the element with high strength/low ductility and the element with low strength/high ductility.

## 1. Introduction

Recently, advanced high strength steels (AHSS) have been increasingly used for automotive parts to improve the fuel efficiency of automobiles by reducing their weight, while ensuring passenger safety. The two most frequently used AHSS in the automotive industry are dual phase (DP) steel and transformation induced plasticity (TRIP) steel. DP and TRIP steels offer good combinations of strength and formability. The mixed microstructure of soft ferrite and hard martensite in DP steel leads to enhanced ductility and work hardening. In contrast, the transformation of metastable retained austenite into martensite during straining in TRIP steel results in improved ductility and toughness.

Resistance spot welding (RSW) is the most widely used method for joining sheet metal parts in the automotive industry. RSW is still the favored process for joining AHSS sheets, although their mechanical and welding properties are very different from low carbon steel sheets [1,2]. In general, AHSS sheets contain a higher amount of carbon and austenitic phase stabilizers, which leads to hard microstructures in the weld region owing to high cooling rates. Consequently, the characterization and evaluation of the mechanical properties and failure behavior of welded joints, particularly for AHSS sheets, are critical issues. The welding characteristics and performance are known to be influenced by various combinations of process parameters. These parameters include weld current and time, the number of impulses, and the electrode force, which have been optimized either by experiments [3–5] or by employing finite element simulations [6,7].

The structures welded by RSW have heterogeneous microstructures, which make prediction of mechanical properties and failure modes challenging. The failure strength and modes at welded joints can be evaluated experimentally by coupon tests [8,9]. There are two failure modes in coupon tests: interfacial failure and pull-out failure. The crack in the first mode penetrates through the weld nugget in a rather brittle failure mode. However, in the latter mode, the crack develops at the base sheet around the weld nugget, leaving a hole in the base sheet. In general, the pull-out failure mode is favored than the interfacial failure mode because of its greater load-carrying capacity and energy absorption as well as its rather ductile failure manner. It is reported that the weld size has a significant impact on the failure mode, and the transition from interfacial to pull-out modes can be obtained by increasing the weld size [10,11]. There have been empirical force-

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based failure criteria for spot welded joints under various combinations of axial and shear loading conditions, but they did not refer to any specifics on the mechanical properties of spot welds or failure modes [12,13].

There have been substantial efforts, both analytical and numerical, in predicting failure behavior in coupon tests. The analytical methods include classical brittle fracture mechanics based approaches to interfacial failure [14,15], lower bound limit load analysis for pull-out failure under combined opening and shear static loading conditions [16–18], and a combination of these two approach for interfacial and pull-out failure [19]. In the numerical approaches, identical properties for the base sheet and the weld nugget assuming rigidity for the faying surface at the welded joint were used to avoid fracture through the weld nugget. Elastic [20], elasto-plastic [21], and elastic-plastic with hardening deterioration by the Gurson model [22,23] are examples of numerical approaches. These simplifying assumptions might be justifiable for mild steel sheets, in which the pull-out failure is favored owing to the low strength of the ductile base sheet. However, more sophisticated failure analysis is required to properly account for the mechanical properties of AHSS sheets, which have a higher strength with relatively lower ductility than those of mild steel sheets [24].

There have been several studies on the microstructures and mechanical properties of spot welded joints of AHSS sheets. The mechanical properties and the microstructures of welded joints of DP and austenitic stainless steels were measured with the Gleeble simulator [25]. Tong et al. [26] and Tao et al. [27] developed a miniature test to obtain stress–strain curves of the heat affected zones (HAZs) and fusion zones (FZs) as well as the base material (BM) by using scanning electron microscopy and digital image correlation techniques. Micro-indentation tests have also been used to determine the toughness and diameter of the FZ [28,29]. In these studies, there were no attempts to investigate the characteristics in failure mode with different combinations of base sheets.

The literature on the RSW of dissimilar combinations and the effect of microstructures on the performance of dissimilar welds is limited. Hernandez et al. [30] investigated the failure mode of dissimilar combinations of DP600-DP780 and DP600-TRIP780. They found that the pull-out failure mode was activated when DP600 was paired with DP780 and TRIP780, and compared the results with the DP600 similar weld. Similar work on the susceptibility of the interfacial failure mode in dissimilar TRIP and non-TRIP steel combinations was undertaken by Hilditch et al. [31]. Marashi et al. [32] investigated the mode of failure and characteristics of FZ for the RSW of austenitic stainless steel and low carbon steel. They concluded that the spot weld strength in the pull-out mode was influenced by the strength and FZ size of the low carbon steel. Transition from interfacial failure to pull-out failure of dissimilar combination of DP600 and low carbon steel was also examined by Pouranvari [33] with varying size of FZ and lap-shear specimen turned out to have greater tendency to fail in pull-out failure than cross-tension specimen. More recently, the effects of the welding parameters on the microstructure, weld nugget size and mechanical properties were analyzed. Wei et al. [34] investigated similar and dissimilar combinations of DP1000 and TRIP980, while Khodabakhshi et al. [35] took a look into those of ultra-fine grained and coarse grained low carbon steel sheets. In their work, the relationship between the microstructure and hardness in different zones of spot welds was established.

The common aspect of the aforementioned efforts is that the failure behavior of weld joints was analyzed without knowledge of the measured properties of welded joints. To overcome the limitations of previous studies, the present authors [36] analyzed the failure behavior of welded structures, especially AHSS sheets, where the failure modes and failure strength of spot welded joints were considered. However, that study focused only on similar welds. In the present study, the critical mechanical properties of dissimilar spot welded joints, including failure properties, were measured by effective experimental procedures that use commonly available facilities such as a universal tensile machine. The key mechanical properties identified by the practical procedure are the hardening behavior and fracture criteria of base sheets and weld nuggets. For the hardening behavior, the strain rate sensitivity as well as the deterioration associated with micro-void development [22,37,38] was characterized along with the fracture criteria. For this purpose, the numerical inverse method [39] was applied to the standard simple tension test for base sheets and miniature simple tension test for the weld nugget. For the fracture criterion, the effective fracture strain, which is dependent on the stress-triaxiality, was utilized by simplifying the original version [40–43] of the damage model [39,44]. The dimensions of the weld nugget were determined using the measured hardness distribution and optical microscopic observation. The characterized properties were then applied to the analysis of the failure behavior in both coupon tests of the lap-shear and U-shape tension tests. Regarding the base material, TRIP980 and DP980 sheets were the AHSS sheets and GMW2 was the conventional mild steel considered. DP980-TRIP980 and GMW2-TRIP980 combinations were utilized in the investigation of dissimilar welded joints.

## 2. Finite element modeling

Mechanical properties and failure performance of spot welded joints were analyzed with finite element (FE) simulations. All constituent materials of the spot welded joints were assumed to be isotropic linear elastic and isotropic hardening rule with von Mises isotropic yield function was adopted. Strain-rate sensitivities were considered only for the base material zones, while the FZs and HAZs of all weld nuggets were assumed to be strain-rate insensitive. Numerical simulations were carried out with a commercial dynamic explicit FE software, ABAQUS/Explicit [44]. For acceptable solution accuracy with computational efficiency, simulations were conducted with a mass scaling which would scale density of the element if the stable time increments were less than a prescribed target time increment. The FE model for each case consisted of three-dimensional eight-node linear continuum elements with a reduced integration (C3D8R). For the simple tension of a standard specimen, the constant cross-head speed of 0.05 mm/s was set as a boundary condition, in which the element size of $0.20 \times 0.20 \times 0.10\ mm^3$ was used for the gauge region of the specimen with the target time increment of 0.001 s. Meanwhile, the speed of 0.0005 mm/s was prescribed as the boundary condition for the simple tension test of a miniature specimen cut from a single spot welded stack which will be introduced in the later section. The element size of $0.048 \times 0.068 \times 0.080\ mm^3$ was used near the center of the welded joint as shown in Fig. 1 with the target time increment of 0.0001 s. With respect to the single welded coupons such as the lap-shear and U-shape tension specimens, the tensile simulation was executed by moving the clamping region of each coupon at the constant speed of 0.02 mm/s as shown in Fig. 2. The simulations adopted the mesh size and the mass scaling scheme comparable to the tension test for the miniature specimen.

## 3. Characterization of mechanical properties

### 3.1. Base sheets

#### 3.1.1. Standard tensile test

Three automotive sheets were considered as the base sheets for RSW joints: TRIP980 (1.2 mm thick), DP980 (1.6 mm thick), and GMW2 (1.2 mm thick). The chemical compositions of the three sheets are listed in Table 1. Different thicknesses involve different amount of rolling, which would affect the microstructure, especially grain structures. The RSW is mainly to assemble completed automotive parts, which often have different thicknesses. Especially when parts are made of different steels, the parts more often than not have different thicknesses. The