

Effects of Heat Affected Zone Softening Extent on the strength of Advanced High Strength Steels Resistance Spot Weld

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Abstract

Resistance spot welds made from Advanced High Strength Steels (AHSS) exhibit Heat Affected Zone (HAZ) softening due to the tempering of pre-existing martensite phase and the consequent decomposition into a mixture of ferrite and cementite. Despite the high strength level for the base metal, the occurrence of HAZ softening may lead to inferior joint strength during Tension-Shear (TS) and Cross-Tension (CT) testing. In this work, we investigated the effects of the HAZ softening on the global loading response for AHSS steels with three different volume fractions of martensite. Microhardness mapping was used as a measure of martensite tempering and extent of softening. Based on the data, the softening was identified in the sub-critical heat affected zone. Hardness drop with the magnitude of 6%, 18%, and 42% was observed in steels with 16%, 52% and 100% of martensite volume fraction (MVF), respectively. In order to model the welded joint loading response using finite element methods (FEM), there is a need to represent the softening in terms of stress-strain relationships. In this work, local stress-strain curves for different weld zones were obtained by scaling the base metal constitutive properties with local hardness ratio. Finite element (FE) simulations of Tension-Shear tests showed that HAZ softening can affect the Tension-Shear load capacity of specimens more significantly when the base metal tensile strength is above 1000 MPa. The paper will discuss the validity of the above finite element approach for describing experimental results and future directions.

Keywords

Advanced High Strength Steels, Resistance Spot Welding, Martensite, Tempering, Finite element method, Failure

Introduction

Advanced High Strength Steels (AHSS) are among the new generation of steels that are being developed to satisfy recent global standards for vehicle safety, fuel economy, and emission requirements. With precisely selected chemical composition and controlled manufacturing process, AHSS possess a combination of strength, ductility, toughness, and fatigue properties due to their complex microstructure consisting ferrite, martensite, bainite, and austenite [1, 2]. Dual-phase (DP) AHSS steels consist of a soft ferrite matrix and hard second phase martensite islands for which increase in steel's ultimate strength is achieved by increasing martensite volume fraction (MVF). For martensitic steels, the entire austenite formed during annealing or hot-rolling transforms entirely to martensite during the quenching process on the run-out table. DP and martensitic steels are AHSS grades that are being widely used in the automotive industry for fabricating auto parts using resistance spot welding technique [1, 3]. Despite having desirable as-received mechanical properties, the existence of metastable phases, particularly martensite, can make AHSS sensitive to higher ranges of temperatures that occur during RSW. Previous researches [4, 5] have shown that in a process, known as martensite tempering, in temperatures between 100 °C and Ac1 line of steel, i.e., in SCHAZ, carbon atoms in carbon-supersaturated martensite microstructure get activated, start diffusing into interlath spacing and dislocations and form clusters, and finally form cementite, e.g. Fe₃C, and coarsen. The final product of this process is tempered martensite consisting ferrite matrix and cementite precipitates, with lower strength, higher ductility, and reduced hardness. This hardness drop is mainly due to martensite tempering, and change in ferrite hardness has been shown to be slight [6]. It has been shown that time and temperature can affect the extent of softening in AHSS containing martensite [4-7]. In these studies, it was shown that increasing the tempering temperatures to regions close to and below Ac1 line or increasing the tempering

time can result in an increase in the extent of softening in SCHAZ. The strength and failure behavior of spot welded joints under specific combined loading conditions, mainly Tension-Shear (TS) and Cross-Tension (CT) loading, have been investigated in several studies, and failure modes were categorized as full and partial interfacial failures (FIF and PIF), round button (RB), and round button in SCHAZ (RBH) failure modes [8-10]. Finite element method has been used as the main computational tool to understand the mechanical behavior of spot welds with particular attention to local deformation and failure characteristics as well as the weld geometry on weld's strength [11-13].

In this work, we initially present the results of hardness measurements performed on spot welds made from different grades of AHSS with different MVF. Hardness drop in each region of the weld is then correlated to the steel's MVF and its carbon concentration. Hardness maps and microstructural analysis are then used to build the geometry of spot weld for FE simulations. The FE models are then partitioned into sections with constitutive behavior obtained by scaling the base metal's true stress-strain curve using the average hardness ratio in the corresponding section. Results from FE simulations are finally compared with those from Tension-Shear testing for the same steels and effectiveness of the FE model with the hardness scaled local stress-strain curves are then discussed.

Experimental Approach

DP and martensitic AHSS sheet steels with a thickness of 1.6 mm and MVF of 16%, 52%, and 100% were selected to study the extent of softening in SCHAZ and its effects on global loading response in Tension-Shear specimens. Steel sheets from similar grades were spot welded together with welding parameters resulting nugget diameters of 6 and 8 mm. The welding procedure, specimens' geometry, and testing conditions were chosen in concert with AWS D8.9 [14]. Some of these weld specimens were cross sectioned in rolling direction and prepared for microstructure analysis and hardness measurements, according to ASTM E3 [15]. Microhardness measurements were performed on the cross section of spot welds with 300 gr load and 15 seconds dwell time. The local hardness drop for each grade, if any, was calculated using the $(H_{BM} - H_{Local})/H_{BM}$ where H_{BM} and H_{Local} are H_{BM} and local hardness. Hardness drop was used later to correlate the extent of softening to steel's chemistry and initial microstructure. The correlations between the extent of softening with steel's carbon content and martensite carbon content (MCC), were then investigated to find which the better representation of softening is. Microhardness maps were also used along with SEM observation to recognize the weld zones and extract weld zones geometry for FE modeling of Tension-Shear testing. BM stress-strain relationship was obtained from uniaxial tensile testing. Local hardness ratio was used to scale the BM stress-strain curve to predict the local constitutive behavior, a required input for computational modeling of Tension-Shear testing.

Computational Approach

Based on the symmetry of the Tension-Shear sample and to minimize the computational time, only one half of the Tension-Shear specimen was modeled in Abaqus commercial FE package. For geometry and boundary conditions for this quasi-static testing, AWS D8.9 standard was used. Using hardness maps and microstructural analysis, spot weld in this three-dimensional model was partitioned into five cells for SCHAZ to allow for assigning loading response of the material in the form of true stress-strain curves by scaling the BM curves with cell's averaged hardness ratio. For fusion zone (FZ), upper-critical (UCHAZ), and inter-critical (ICHAZ) one cell was created. For DP590, since ICHAZ was wider than the other two steel grades and hardness variation was larger, two cells were used to allow for a smoother transition in material properties. It was assumed that this method of partitioning results in more realistic results for global loading response in comparison with using a single partition for HAZ regions. Typical meshing based on tetrahedron elements with proper refinement was performed to ensure solution converges. **Figure 2** shows a view of the mesh design along with hardness map, partitions, and hardness ratio. In this work, FE models with softening and without softening in SCHAZ were used to understand how HAZ softening impact spot weld strength.

Results and Discussion

Softening Extent in SCHAZ of Spot Welds

Results from hardness measurements from FZ, SCHAZ, and BM are brought in **Figure 1** (a) for comparisons. From these results, it was observed that BM hardness increases proportionally as the MFV increases. It was

also observed that when MFV in BM decreases from 100% to 52% and 16%, for M1700, DP980, and DP590, respectively, the hardness ratio of FZ increases, significantly. This indicated the effect of base metal MFV on the hardness of the FZ. Comparing results for the SCHAZ, as shown in **Figure 1** (b), shows that as the MVF increases the hardness drop in this region increases. For DP590, DP980, and M1700 with 16%, 52%, and 100% martensite in the initial BM microstructure, the hardness drop was measured to be 6%, 18%, and 42%, respectively. This indicated that a direct correlation could be made between the MVF and hardness drop as illustrated in **Figure 1** (b). For DP590 the softening is very low due to the small amount of martensite phase in the microstructure. The severe softening in M1700 is clear and a result of higher MVF in this fully martensitic steel. Trends of plots in **Figure 1** (b) show that the softening extent can be predicted more accurately by using both MVF and MCC. Here and for example, we multiplied MVF by MCC and added results to **Figure 1** (b). This new plot suggests that a better correlation can be made by combining both these two parameters, i.e., MVF and MCC, for the prediction of softening extent. However, more investigations are needed to understand this relationship with more details. Results from micro-hardness mapping were also used to build the spot weld geometry in computational models. These results and partitions created for spot weld zones along with the mesh on the cross section for DP590 and M1700 spot welds were presented in **Figure 2**, in the earlier section. As explained previously, the local constitutive behavior for each region of the weld was obtained by scaling the true stress-true strain curve of BM by the average hardness ratio of that region.

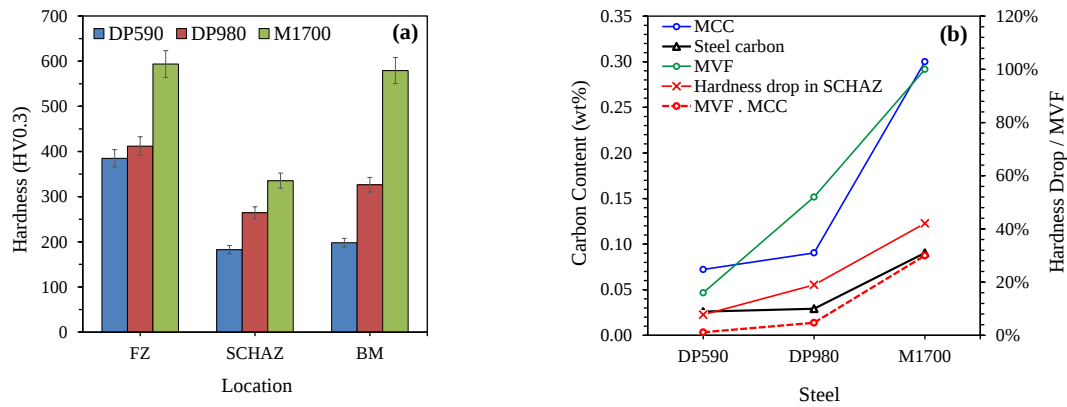


Figure 1: Hardness values in three regions of spot weld for steels used in this study (a), Correlation between hardness drop and MVF and carbon content (b).

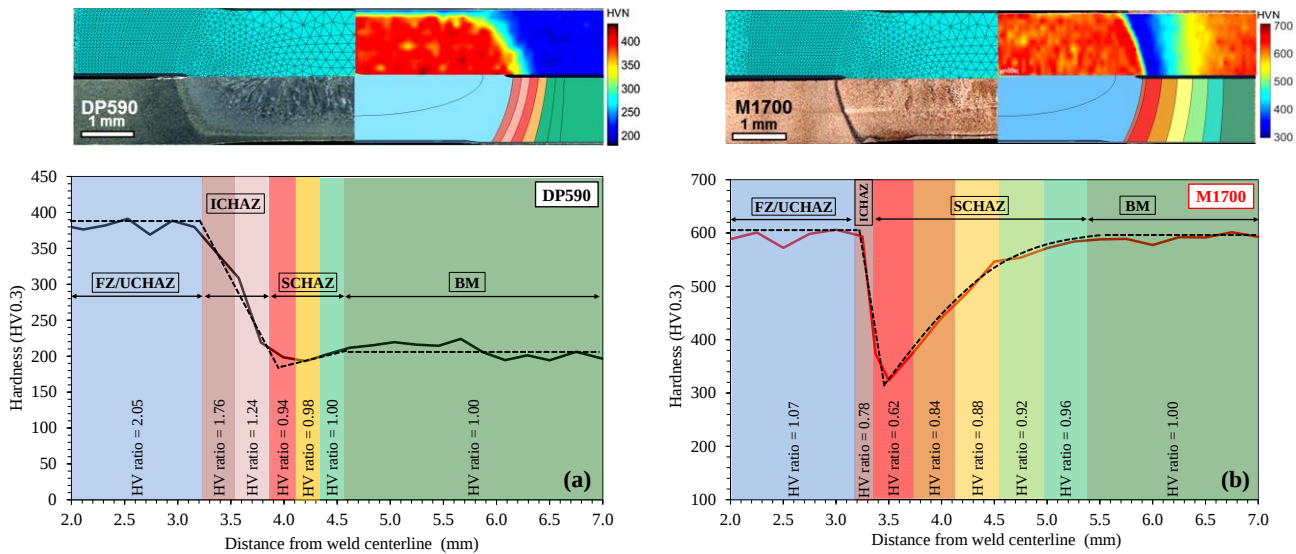


Figure 2: Hardness maps, partitioned HAZ with local constitutive behavior, and mesh design for Tension-Shear FE models for DP590 (a) and M1700 (b).

Effects of SCHAZ Softening on Tension-Shear Global Response

Finite element simulations were run for Tension-Shear models built for DP590, DP980, and M1700 spot welds with nugget diameter (ND) of 6 mm for models with and without softening in HAZ and results are presented in **Figure 3** (a). One observation from these results is that the maximum load at failure point increases as the MVF increased in both experimental and computational work. From this result, it is observed that the max load at failure has 5%, 17%, and 34% error, for DP590, DP980, and M1700, respectively. This increase in error can be explained by the extent of softening meaning that as the extent of softening increases, the error in results from computational modeling increases as well. This hardness ratio was used to scale the BM properties and also the weld zones were partitioned into a discrete number of the zone. In addition to these, hardness ratio was averaged through each partition.

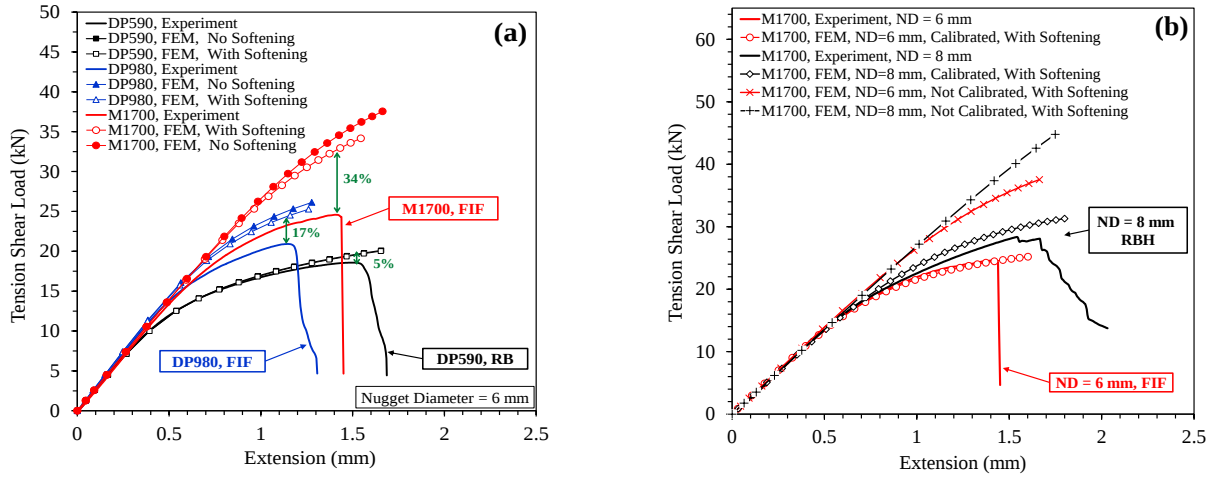


Figure 3: Results from FE simulation and experiments for DP590, DP980, and M1700 ND of 6 mm (a) and M1700 with ND of 6 and 8 mm (b).

In contrast with the FE model, real weld has material changes smoothly through and between zones. Therefore, these errors can be acceptable with simplifications that have been used in this study. Another observation from **Figure 3** (a) can be the difference between load from weld with softening and that from weld without softening. As it can be seen, as the extent of softening increases, this difference increases as well. This implies that when the base metal has higher MVF, the impact of the maximum load for the welded joint reduces more when compared with simulations without SCHAZ softening. This, of course, is valid for this specific ND. From FE simulations, the difference between load at experiments failure for a model with, and the one without HAZ softening is 0%, 3%, and 7% for steels with 6%, 18%, and 42% hardness drop in SCAHZ. For AHSS with BM strength above 1000 MPa, this difference is considerable, and therefore accurate measurements of local constitutive properties especially for SCHAZ become more critical. In another attempt to study how the softened-SCHAZ and ND can affect the weld strength, the model for M1700 spot weld was calibrated by using hardness ratios less than measurements, for SCHAZ cells and modified stress-strain curves for these cells were assigned to the FE model and simulations were run for welds with softening in SCHAZ. The results from recent simulations are plotted in **Figure 3** (b) along with those from experiments. FE simulations show that after calibrating the model for M1700 spot weld with ND of 6 mm, model is able to predict the load-extension curve for the weld with 8 mm ND better but not overlapping with experiment. This shows that if the representative local properties are available, the model can predict the loading response for both nugget diameters and failure modes more accurately.

To understand the role of ND and softened SCHAZ on failure mode of the spot weld, the equivalent plastic strain (PEEQ) at the notch and SCHAZ inner edge for M1700 spot welds with 6 and 8 mm ND are plotted in **Figure 4** (a). Results from experiments showed that failure mode for weld with ND of 6 and 8 mm are FIF and RBH, respectively. Comparing PEEQ at notch and SCHAZ in **Figure 4** (a) shows that PEEQ at SCHAZ for ND of 6 mm is similar to the notch. Considering PEEQ as a parameter that can be used to evaluate the failure mode, this indicates that for the 6 mm, material in notch will reach the failure criterion that can cause crack initiation, growth and finally failure in FIF mode. Using the same approach for weld with 8 mm ND, it

can be seen that PEEQ in SCHAZ is significantly higher than that in notch indicating that material in this region meets the plastic failure strain before notch leading to necking in sheet thickness and finally failure in RBH mode. Another observation from FE simulations was made based on the cross section inplane shear stress in the center of FZ for welds with 6 and 8 mm ND. Results are presented in **Figure 5**. As it can be seen, for weld with ND of 6 mm, shear stress increases significantly as the extension increases while for that with ND of 8 mm this curve is smoother with a lower magnitude. It was also observed that for weld with ND of 6 mm that failed with FIF mode, the in-plane shear stress is significantly higher than that for ND of 8 mm where failure happens at SCHAZ.

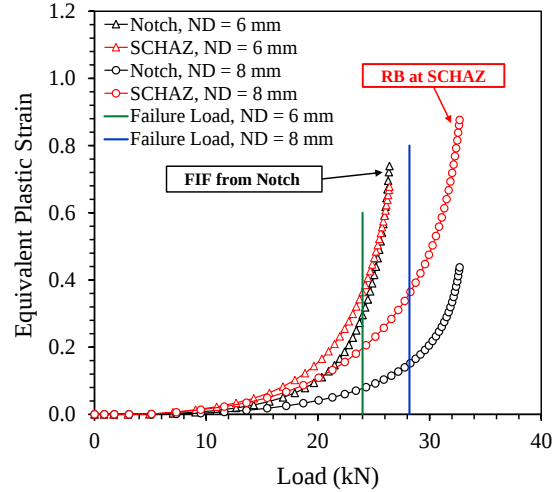


Figure 4: Equivalent plastic strain at the notch and SCHAZ for M1700 Tension-Shear specimen with nugget diameters of 6 and 8 mm.

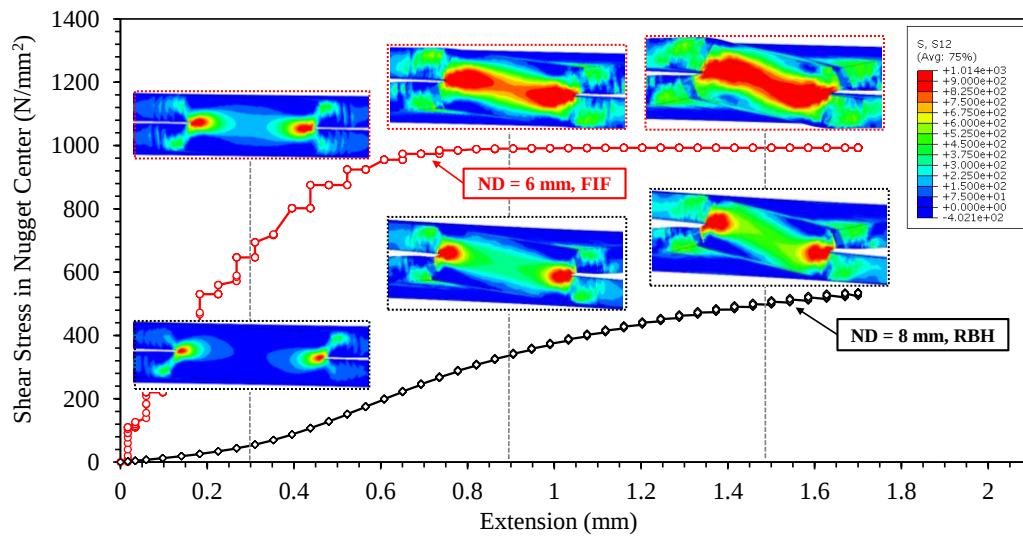


Figure 5: In-plane shear stress on the cross section of tensile-shear spot weld and in the center of nugget for M1700 Tension-Shear specimen with nugget diameters of 6 and 8 mm.

Conclusions

Based on the data from microhardness measurements, softening was identified in SCHAZ. The hardness drops with the magnitude of 6%, 18%, and 42% was observed in steels with 16%, 52% and 100% of martensite, respectively. The hardness ratio evaluated and used to represent as the extent of softening.

Maximum hardness drop was observed in SCHAZ close to the Ac1 line. Hardness drop increases as steel's carbon content, MVF, and MCC increase; however, it was found that a combination of MVF and MPC could be used to predict better the hardness drop or extent of softening in SCHAZ.

FE model for the Tension-Shear test with partitioned and calibrated weld zones is able to predict the global deformation behavior of specimens when the extent of softening in SCHAZ is negligible, for instance, in spot weld made from DP590. In steels with greater extent of HAZ softening, e.g., DP980 and M1700, the contribution of SCHAZ and its local constitutive behavior increases in the prediction of deformation response.

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