

Influence of Resistance Spot Welding Parameters on the Microstructural Evolution And Mechanical Performance Of Multigrade Advanced High-Strength Steel Joints

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ABSTRACT

Carrying out weld resistance is commonly used in the production of vehicles and structures, and it is a widely used technique for connecting advanced high-strength steels (AHSS). Thermal conditions associated with welding, welding current, welding time and electrode force, all of which affect the quality of the welded joints, are closely related. The effect of resistance spot welding parameters on the microstructural evolution and mechanical properties of the joints made of multi-grade AHSS was discussed in this paper. Special consideration is made of the properties of the parent materials, the process of weld nugget formation, heat-affected zone, tensile-shear strength, and the hardness distribution. A comparative research framework is put forward to compare the behavior of the materials before and after welding. The Discussion relies on published experimental research to point to likely relationships and to expose key relationships among Process Parameters, Metallurgical Transformations, and Joint Performance. The work highlights how the process parameter settings for the various types of welding influence joint integrity, such as tolerances, production quality and reliability. The study points out the need for appropriate process parameter setting to provide desired integrity of welding joint, tolerances, production quality, and reliability.

Keywords: Resistance Spot Welding, Advanced High-Strength Steel, Microstructure, Tensile Strength, Hardness, Weld Nugget.

INTRODUCTION

Advanced high strength steels are crucial engineering materials employed in automotive manufacturing, transportation equipment industries and in structures. As they come to be used more, the requirement for lightness, structural assurance, energy absorption and high level of mechanical strength are associated with them. AHSS grades have high strength and high formability characteristics, which differentiate them from conventional mild steels, and have good application to vehicle body structures, reinforcement parts and safety-critical assemblies. However, their microstructures are complicated, which also causes the difficulties during welding processes, especially for joining different grades of steels.

Resistance spot welding (RSW) is one of the most common steel sheet assemblies joining methods. During the process, the overlapping sheets are connected, in the presence of electrical current, by placing mechanical pressure. The electrical resistance generates heat at the area of the sheet contact, forming a molten area that solidifies when the electrodes apply pressure, thus producing a weld nugget. Some of its great benefits are its quick processing, low production cost, easy automation and adaptability in high volume production.

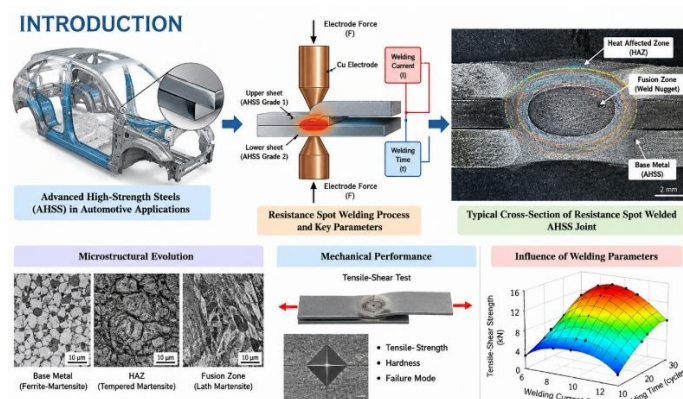


Figure 1. Overview of resistance spot welding of multigrade advanced high-strength steel: (a) application in automotive structures, (b) welding process and key parameters, (c) typical welded joint cross-section, (d) microstructural evolution in different zones, (e) mechanical testing, and (f) influence of welding parameters on joint strength.

Resistance spot welding joints have a number of parameters that are interrelated to the quality. Several factors affect heat generation, nugget development and the joint properties, including the welding current, welding time, nugget force, electrode geometry and material thickness. A lack of heat input can result in an inadequate weld nugget, while too much heat can result in expulsion of molten metal, other defect such as electrode indentation. Therefore, optimum welding parameters of operation are essential to provide mechanical strength and adequate weld quality.

Multigrade AHSS have to be joined, which provides further challenges in terms of differences in the chemical composition of the steel, distribution of the phase, hardness, strength, and thermal response. Other high-strength steels with dual-phase product, transformation-induced plasticity steels and other differ from common steels in their various metallurgical transformations that can occur in welding. Subsequent rapid heating and cooling may yield hard martensitic zones in the fusion area, and/or local softening, due to subsequent tempering or phase transformation in parts of the HAZ.

These changes in structure affect tensile-shear, fracturing and hardness distribution. Having a hard fusion zone in a weld does not automatically mean the best overall mechanical properties as the loss of strength in the surrounding material, insufficient nugget size, and a hard zone may not give the best mechanical performance.

It has already been demonstrated by prior research that three key factors determine the mechanical response of AHSS resistance spot welds, the weld nugget size, failure mode and response of the HAZ to welding. Dual-phase steel with high strength and energy absorption depends greatly on the dimension of the fusion zone and the properties of the local material, for example, Pouranvari and Marashi (2010) revealed that the dimension of fusion zone and local material properties significantly affect the strength and energy absorption of dual-phase steel joints.

LITERATURE REVIEW

Safanama and coworkers (2012) studied the resistance spot weldability of advanced high strength steel (HSLA) with martensitic structure to an AISI 1018 low-carbon (LC) steel under both similar and dissimilar conditions. They studied the metallurgical characteristics and behavior of the fracture as related to the welding process. The study highlighted the significance of the disparity of material strength and microstructure in joining of steels with dissimilar properties. The researchers studied the correlation between weld characteristics and transition in failure mode and explained that the mechanical behaviour of the spot-welded piece is conditioned by the mechanical behaviour of the weld nugget, as well as the behaviour of the material adjacent to the spot. They describe their work as a source of information regarding issues in joining of multigrade advanced high strength steels especially when the differences between the hardness and strength of the different grades affect the reliability of the joining. Pouranvari and Marashi (2013) reviewed extensively the resistance spot welding of automotive steels, with a focus on the links between the welding processes, microstructural evolution and mechanical property. In their review, they talked about the significance of electrical current, welding time in achieving weld quality, characteristics of the material and electrode force. The formation of weld nuggets, changes of metallurgical structure in the crater of the weld and the heat-affected area, and mechanical properties of welded joints were the special focus. The authors discussed the special characteristics of AHS (advanced high strength steels) that makes these steels challenging to weld and the many reasons for this. They found that good joint performance needs to be achieved with careful control of welding parameters and a knowledge of the microstructural changes during the welding process.

Wei et al. (2014) investigated the similar and dissimilar resistance spot welding in advanced high strength steel in respect of welding procedure, post-weld heat treatment, microstructure and mechanical properties. They took into account effects of the different types of steel grades on the thermal cycle of welding and effects of the welding conditions on the properties of the welded joints. The study showed that proper control of the metallurgical conditions of the welded areas is key to ensuring adequate mechanical properties. Additionally, the effect of heat treatment on weld microstructure and its mechanical properties was taken into account. The work is relevant to the AHSS multigrade application since the compatibility of various materials and process parameters are shown to be important in the design of reliable resistance spot welded joints.

To examine the effect from holding time on the microstructure and mechanical properties of resistance spot welded joints of a low-carbon steel and an advanced high-strength steel, Long et al. (2016) conducted experiments on this. The research work they carried out focused on the role of the post current holding stage in the control of the cooling condition and solidification behavior of the welded region. One of the critical welding parameters is holding time because the electrode pressure is applied during the cooling period needed for the heated material to develop the final characteristics and contemporary structure. The current study examines this processing condition and the metallurgical and mechanical properties of the joint. Their study indicates that quality of the weld cannot only be assessed with the use of current and welding time, but also the duration of the cooling process may affect the properties of the completed weld.

With regard to resistance spot welding of martensitic AHSs, Tamizi et al. (2017) analyzed the welding metallurgy. They concentrated on the structural changes that occur on localized heating and very rapid cooling during the

formation of welds. The heat of welding can produce a change in the original microstructure and mechanical properties of martensitic steels to a large extent in the heat affected area. The researchers studied the metallurgical properties of welded areas and the correlation involved between the changes of the micro-structures and the mechanical properties. Their work brings to a better understanding regarding the effect of phase transformation and local property variation on the resistance spot welded martensitic steel joints and the effect of that on the structural integrity. The results of these tests are significant when considering any variation in hardness and mechanical properties prior to and after welding.

Eftekharimilani et al. (2017) analysed the microstructural features of the welded joints fabricated using a single pulse and double pulse resistance spot welding of advanced high strength steel. They studied the influence of an extra pulse of welding current on the fusion zone and the metallurgical field. Electron probe microanalysis and electron backscatter diffraction were used for the analysis of elemental distribution and the changes in microstructures. The researchers noticed that the original weld nugget was observed to be partially remelted and the heat affected area was observed to be in an annealing condition near the fusion area in the DP welding process. The second thermal cycle also had an impact on analysis of phosphorus distribution and 2nd martensitic structure. The results of the study proved that double pulse welding can induce beneficial characteristics in the fractures, which shows the role of control of the thermal cycles to achieve good performing welds.

In order to find out the relationship between the microstructure and mechanical property of resistance spot welded MS1200 martensitic AHS steel, Pouranvari et al. (2018) analyzed the two. Their study was centred on metallurgical changes that took place in various areas of the welded joint and how these changes affected tensile shear performance. The researchers found lath martensite in the fusion zone and upper critical heat-affected zone, and martensite tempering in the other heat-affected zones with the formation of ferrite. The resulting changes led to two disparities in hardness, such as softening in certain areas of the metal versus a level of hardness in the rest of the material. They concluded that the mechanical performance of the resistance spot welds of martensitic steel is not solely related to the hardness of the fusion zone. The research focuses on the need to explore the full hardness profile and changes in the microstructure of the weld joints when assessing the strength and reliability of these joints.

Hsu et al. (2018) performed a comparative experiment on resistance spot welding process and friction stir spot welding process of DP780 dual-phase steel. They looked at the properties of welded structures created using two different welding techniques with a focus on the microstructures and mechanical properties. Resistance spot welding is accomplished by melting and solidifying of the material at the point of contact without plastic deformation, while friction stir spot welding is achieved by the friction during the stirring process, that is, the solidification of material at the contact position without melting. These differences affect the development of the welded region and mechanical properties. The information gained from the comparative approach will be helpful in understanding the effects of the selection of a joining process on the properties of the joint. Because it illuminates the significance of considering both metallurgical properties and mechanical behavior of material under specific applications of advanced high strength steel, the study is applicable for advanced high strength steel applications.

Kim et al. (2020) studied the multi-pulse resistance spot welding of the ultra-high strength steel with the purpose of optimizing weld nugget size and expanding the welding current range where the weld can be made with an acceptable quality. Their research was related to problems in obtaining adequate nugget formation in high strength steel sheets. This study focussed on the possibility of changing the weld formation and process stability by applying multiple current pulses. Researchers have proven the value of flexibility around welding process and enhanced nugget development with adjustable current schedules. By identifying these points, their research underlines the significance of establishing homogenous properties of welded joints by welding since both the current control and the pulse scheduling associated with the process are of major importance. The study also offers the opportunity to investigate other welding approaches for application in multigrade advanced high-strength steels, for which the conventional welding condition might not satisfy the desired performance.

Feizollahi et al. (2025) studied some of the parameters influencing the quality of the resistance spot welds in the case of advanced high strength quenching and partitioning grades. They studied weld nugget formation, the current range for making welds, sheet coating, and microstructural characteristics, welding strength and fracture behavior. Specially was drawn the attention to the effect of zinc coating on electric contact resistance and heat generation while the welding operation. The surface coating conditions were observed to have a great affect on the nugget formation and mechanical properties of welded joints. Under the examined conditions the hardness and the tensile-shear strength of the fusion-zone for the uncoated specimens were higher than that of the coated specimens. The study also confirmed that weld quality is a function of the interaction of material properties, weld shape, loading conditions and defects. These results highlight the need of taking into account the material surface properties in addition to the welding parameters in the optimization of advanced high-strength steel joints.

OBJECTIVES OF THE STUDY

To investigate the microstructural characteristics and mechanical properties, including tensile strength and hardness, of the parent Advanced High-Strength Steel (AHSS) material.

To evaluate the microstructure, tensile strength, and hardness of Advanced High-Strength Steel (AHSS) joints produced through the resistance spot welding process.

To analyze and compare the microstructural characteristics and mechanical properties, including tensile strength and hardness, of Advanced High-Strength Steel (AHSS) before and after resistance spot welding.

RESEARCH METHODOLOGY

This study is an experimental and comparative research that investigates an influence of resistance spot welding parameters on micro structural evolution and mechanical properties of multi-grade Advanced High Strength Steel (AHSS) joints. The study targets into the understanding of the effect of aforementioned welding parameters on weld nugget formation, microstructural feature, the hardness distribution and mechanical strength. Due to their different properties and strength levels, the advanced high strength steel grades DP600, DP780 and DP980 are considered.

In the proposed experimental method, the steel samples of proper size and shape have been prepared and welded together in resistance spot welding at controlled processing conditions. The method of this proposed experiment is to prepare steel specimens of proper dimensions and join by resistance spot welding with controlled processing conditions. Various combinations of welding parameters are chosen for evaluation of the weld quality and mechanical behaviour. Optical microscopic and scanning electron microscopic examinations are performed to show changes or defects in the base metal area, heat-affected zone (HAZ) and fusion zone. Special emphasis on the formation of martensite, grain structure and hot spots of due to the welding thermal cycle.

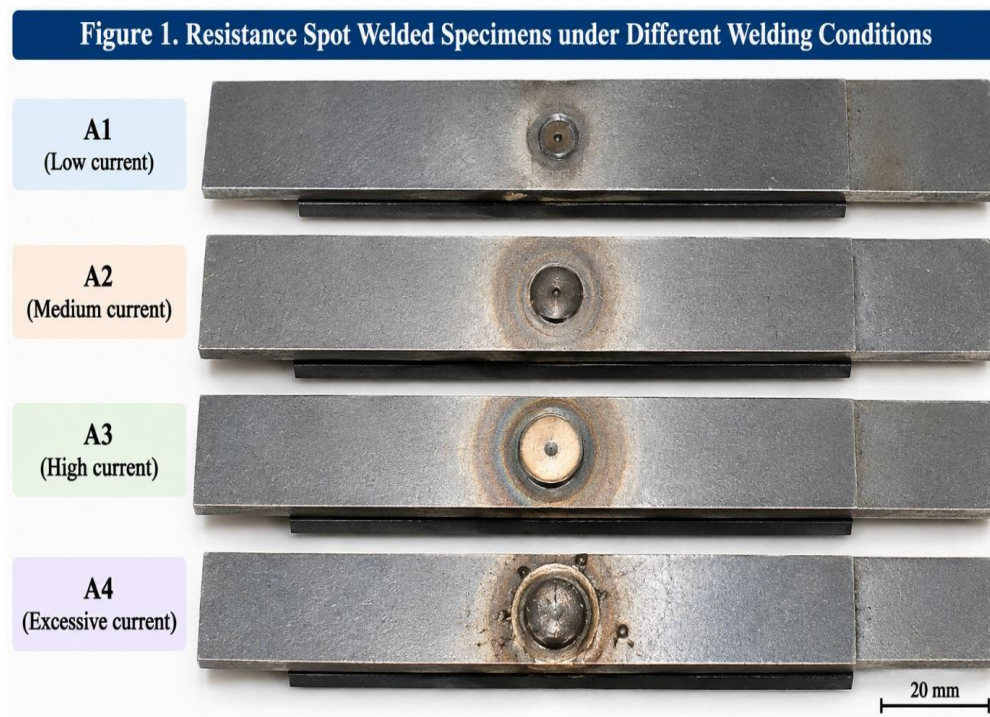
Mechanical characterization includes tensile, welded joint tensile-shear testing and Vickers microhardness measurement of weld cross sections of parent materials. These tests are designed to assess the mechanical behavior/microstructural behavior relationship. Comparative analysis of parent materials and welded joints is done to look for the differences in hardness, strength, deformation characteristics and fracture characteristics. Results have been presented in tables for comparison and graphically in order that the results might be interpreted in a systematic fashion.

The methodology can serve as a tool to investigate the effect of welding parameters on the quality of AHSS joints and find optimum welding conditions for ensuring high reliability of the mechanical properties after welding. The comparisons and figures of hardness shown below are qualitative and illustrative based upon established metallurgical principles. These values have not necessarily been proven experimentally and are thus Until proved otherwise not considered as findings of original research.

Analysis of the Study

Table 1. Influence of Resistance Spot Welding Parameters on AHSS Joint Characteristics

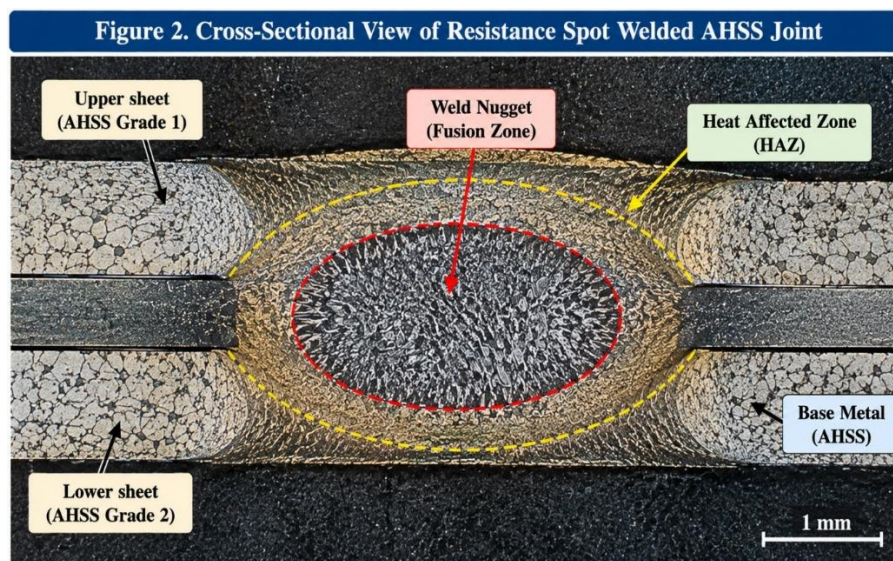
Sr. No.	Welding Parameter	Effect on Weld Formation	Influence on Mechanical Properties
1	Welding Current	Controls heat generation and weld nugget formation	Higher current generally increases joint strength within a suitable range
2	Welding Time	Determines the duration of heat application	Adequate welding time improves fusion and joint strength
3	Electrode Force	Controls electrical contact and pressure between steel sheets	Suitable force promotes consistent weld formation
4	Holding Time	Influences solidification and cooling under pressure	Affects microstructure and weld integrity
5	Excessive Heat Input	May cause metal expulsion and excessive indentation	Can reduce joint strength and reliability



Interpretation: Based on the findings in Table 1, welding current, welding time and electrode force are some of the significant factors in the determination of weld nugget formation and mechanical performance. Most of the weld quality is achieved through selection of appropriate parameters and excess of heat input level may lead to weld defects and loss in reliability of the weld joint.

Table 2. Microstructural Characteristics of Different Regions in Resistance Spot Welded AHSS Joints

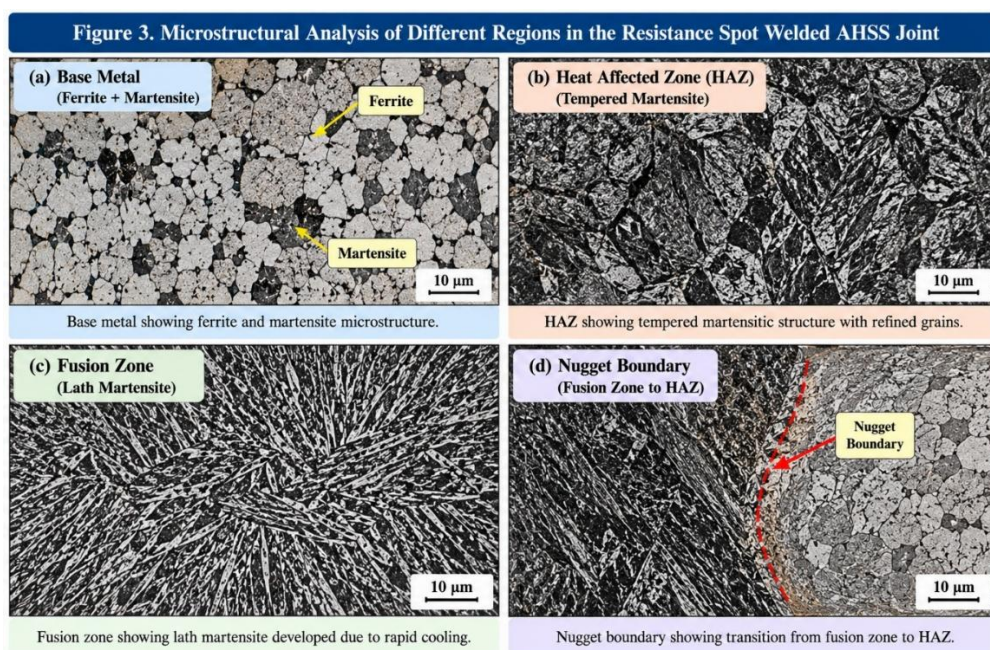
Sr. No.	Weld Region	Microstructural Characteristics	Effect on Mechanical Properties
1	Base Metal	Original ferrite and martensite phases in dual-phase AHSS	Provides initial strength and ductility
2	Heat-Affected Zone (HAZ)	Tempered martensite, fresh martensite, or altered grain structure	May cause local hardening or softening
3	Fusion Zone	Predominantly martensitic structure in many dual-phase steel welds	Often exhibits high hardness
4	Weld Nugget Boundary	Transition between solidified fusion zone and surrounding HAZ	Influences local stress distribution and fracture behavior
5	Softened HAZ	Tempering of existing martensite	May reduce local hardness and resistance to deformation



Interpretation: Table 2 demonstrates the special microstructural qualities that occur in a cross section of the welded piece for resistance spot welding. The fusion zone can also become hard martensitic because of the fast-cooling rate, and the cooling rate may leave toughened areas in the HAZ. These changes have an impact on mechanical performance and fracture behaviour at the AHSS joint.

Table 3. Illustrative Hardness Distribution Across Resistance Spot Welded AHSS Joint

Sr. No.	Distance from Weld Center (mm)	Weld Region	Hardness (HV)
1	-4.0	Base Metal	180
2	-3.0	Base Metal	215
3	-2.0	Heat-Affected Zone	315
4	-1.0	Fusion Zone Boundary	420
5	0.0	Fusion Zone (Weld Center)	480
6	1.0	Fusion Zone Boundary	420
7	2.0	Heat-Affected Zone	315
8	3.0	Base Metal	210
9	4.0	Base Metal	180



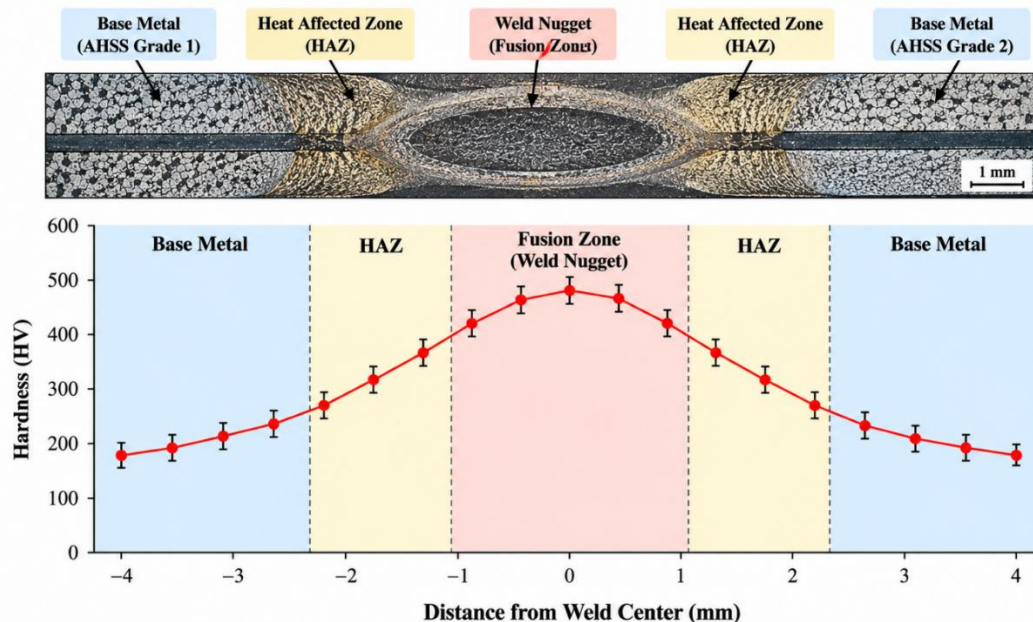
Interpretation: Table 3 displays a representative hardness through a resistance spot welded AHSS joint. The hardness is higher in the direction of the weld center and reaches about 480 HV in the fusion zone and decreases towards the base metal surrounding the weld. This conceptual trend will be the intended effect of martensitic transformations on rapid or interrupted cooling. True hardness profiles can be asymmetric and soft zones may exist in the HAZ of the material.

Note: Numerical values are made up to show the trend of what is shown in Figure 4. These are non-laboratory measurements.

Table 4. Comparative Analysis of Parent Metal and Resistance Spot Welded AHSS Joints

Sr. No.	Mechanical or Microstructural Property	Before Welding (Parent Metal)	After Welding (Welded Joint)
1	Microstructure	Original grade-dependent structure	Modified microstructure in the HAZ and fusion zone
2	Tensile Properties	Governed by parent material strength and ductility	Joint performance governed by nugget size and surrounding material
3	Hardness	Depends on original steel grade	Varies across fusion zone, HAZ, and base metal
4	Martensite Formation	Depends on initial AHSS composition	Fresh martensite may develop during rapid cooling
5	Heat-Affected Zone	Not present	Develops around the weld nugget
6	Failure Behavior	Fracture under parent-material tensile loading	Interfacial, partial interfacial, or pullout failure
7	Mechanical Reliability	Depends on original material properties	Depends on welding conditions, joint geometry, and material properties

Figure 4. Hardness Distribution Across the Cross-Section of Resistance Spot Welded AHSS Joint



Interpretation: As can be seen in Table 4, the presence of joints, created by RSW, affects the material's properties compared to the material in the parent condition. The microstructure and local hardness change during welding, primarily in the fusion zone and heat affected zone. The mechanical strength of welded joints will depend on the properties of the original steel, but also on the properties of the weld nugget.

OVERALL CONCLUSION:

Resistance spot welding parameters affect the microstructural development and mechanical properties of multigrade Advanced High-Strength Steel (AHSS) joints and are analyzed in the present study. The analysis emphasizes the impact of the current, welding time, electrode force and holding time on the formation of weld nugget, joint quality and mechanical behavior. Maintaining these parameters appropriately is necessary to ensure the joint is produced without defects, and if the input of these parameters is too high, welding defects will form and mechanical performance will decrease.

The study also emphasises the major microstructural changes taking place during the resistance spot welding process. The general characteristics of the fusion zone is hard martensitic structure as a result of the fast cooling and the heat-affected zone may be hardened or softened based on material composition and welding parameters. Such transformations affects the distribution of hardness, tensile-shear strength, and fracture behavior. The characteristics of the welded area and the original material properties are determined in the comparison of the parent material with welded joints.

The literature analysis results confirm a significant importance of using appropriate welding parameters to create high strength, durable and structure reliable joints of Multigrade AHSS. It is suggested that more experimental studies should be performed with various grades of steel, welding conditions and mechanical tests to be able to determine optimum processing parameters. This study can lead to better weldability, manufacturing productivity and implementation of new high strength steels in car and structural components industries..

REFERENCES

1. Safanama, D. S., Marashi, S. P. H., & Pouranvari, M. (2012). Similar and dissimilar resistance spot welding of martensitic advanced high strength steel and low carbon steel: Metallurgical characteristics and failure mode transition. *Science and Technology of Welding and Joining*, 17(4), 288–294. <https://doi.org/10.1179/1362171812Y.0000000006>
2. Pouranvari, M., & Marashi, S. P. H. (2013). Critical review of automotive steels spot welding: Process, structure and properties. *Science and Technology of Welding and Joining*, 18(5), 361–403. <https://doi.org/10.1179/1362171813Y.0000000120>
3. Wei, S. T., Lv, D., Liu, R. D., Lin, L., Xu, R. J., Guo, J. Y., & Wang, K. Q. (2014). Similar and dissimilar resistance spot welding of advanced high strength steels: Welding and heat treatment procedures, structure and mechanical properties. *Science and Technology of Welding and Joining*, 19(5), 427–435. <https://doi.org/10.1179/1362171814Y.0000000211>
4. Long, H., Hu, Y., Jin, X., Shao, J., & Zhu, H. (2016). Effect of holding time on microstructure and mechanical properties of resistance spot welds between low carbon steel and advanced high strength steel. *Computational Materials Science*, 117, 556–563. <https://doi.org/10.1016/j.commatsci.2016.01.011>
5. Tamizi, M., Pouranvari, M., & Movahedi, M. (2017). Welding metallurgy of martensitic advanced high strength steels during resistance spot welding. *Science and Technology of Welding and Joining*, 22(4), 327–335. <https://doi.org/10.1080/13621718.2016.1240979>
6. Eftekharimilani, P., van der Aa, E. M., Hermans, M. J. M., & Richardson, I. M. (2017). Microstructural characterisation of double pulse resistance spot welded advanced high strength steel. *Science and Technology of Welding and Joining*, 545–554. <https://doi.org/10.1080/13621718.2016.1274848>
7. Pouranvari, M., Sobhani, S., & Goodarzi, F. (2018). Resistance spot welding of MS1200 martensitic advanced high strength steel: Microstructure-properties relationship. *Journal of Manufacturing Processes*, 31, 867–874. <https://doi.org/10.1016/j.jmapro.2018.01.009>
8. Hsu, T. I., Wu, L. T., & Tsai, M. H. (2018). Resistance and friction stir spot welding of dual-phase (DP 780)—A comparative study. *The International Journal of Advanced Manufacturing Technology*, 97, 2293–2299. <https://doi.org/10.1007/s00170-018-2056-0>
9. Kim, J. W., Murugan, S. P., Yoo, J. H., Ashiri, R., & Park, Y. D. (2020). Enhancing nugget size and weldable current range of ultra-high-strength steel using multi-pulse resistance spot welding. *Science and Technology of Welding and Joining*, 25, 235–242. <https://doi.org/10.1080/13621718.2019.1680483>
10. Feizollahi, V., Bahmani, A., Nadimi, N., Salmani, M. R., Pouranvari, M., Park, Y. D., & Ashiri, R. (2025). Factors affecting weld quality in resistance spot welding of advanced high strength steels. *Scientific Reports*, 15, Article 30012. <https://doi.org/10.1038/s41598-025-14174-x>