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Original Research Paper

Effect of Resistance Spot Welding Parameters on the Microstructure and Mechanical Properties of Multigrade Advanced High-Strength Steel Joints"

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Abstract: Tap on Advanced High Strength Steels (AHSS) materials, which are already widely adopted in automotive and structural applications, due to their high strength, good ductility and ability to provide weight reduction of the parts. Resistance Spot Welding (RSW) is one of the most popular methods for welding AHSS sheets. But the welding parameters including welding current, welding time, and electrode force and hold time have a significant effect on the weld nugget and HAZ morphology and characteristics. This work potentially studies the influence of resistances spot welding parameters on microstructure and mechanical properties of multipurpose AHSS joints. The parents and spot-welded joints are characterized with respect to their microstructures, tensile-shear strength and hardness. The characteristics of materials before and after welding and the relationship between welding parameters, evolution of microstructures and characteristics of the welding joints are compared. The expected results will serve as valuable data to determine optimal RSW parameters to make reliable joints with enhanced mechanical properties of AHSS materials.

Keywords: Advanced High-Strength Steel, Resistance Spot Welding, Welding Current, Welding Time, Electrode Force, Microstructure, Tensile Strength, Hardness, Heat-Affected Zone, Weld Nugget.

Introduction:

Advanced High-Strength Steels (AHSS) use in automotive body parts or vehicle structures has grown, as done to improve the lightness, safety, and fuel economy of vehicles. Higher strength than conventional Low Carbon Steels are offered by AHSS grades like Dual Phase (DP), Transformation-Induced Plasticity (TRIP), Complex Phase (CP) and Martensitic Steels. Different grades of AHSS may be used within a single construction, typically referred to as "multigrade AHSS," enabling engineers to create the desired mix of features and attributes, such as strength, ductility, crash resistance and weight reduction.

The Resistance Spot Welding technique is widely adopted in the joining of sheet metal components as it is fast, consumes little material, and can be easily automated. During RSW process, a current with frequency upon the application is flowing and electrical resistance at the interface of two sheets produces heat where the magnitude depends on the welding current, the electrical resistance and the process time. Heat generated forms a molten weld nugget which then cools down when the electrode pressure is applied.

Welding process the microstructure of AHSS may be significantly altered. Rapid heating and cooling can cause the formation of martensite and other transformed phases in the fusion zone and heat affected zone. The changes may have an impact on properties such as hardness, tensile-shear strength, failure mechanism, ductility and overall joint counterpart reliability. Hence, the control of welding parameters becomes significant especially when welding between the various grades of AHSS.

In the present study, the effect of resistance spot welding parameters on the microstructure and mechanical properties of the multigrade AHSS joints were studied. The study takes into consideration the parameters of the metal obtained from the parent material and welding parameters, and compares the characteristics of the microstructures, tensile and hardness of these metals.

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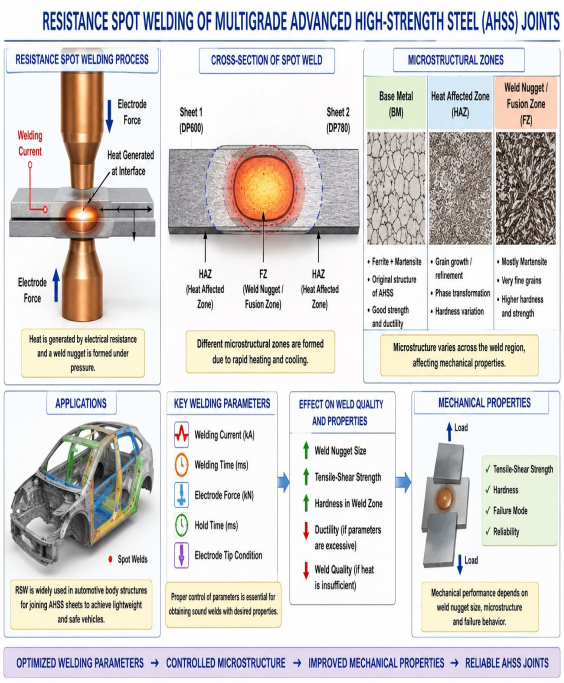


Review of Literature:

Smith & den Uijl (2006) investigated the resistance spot welding of advanced high strength steels primarily with automotive applications in mind. They gave an explanation that although there is high strength but AHSS have low material weight, therefore appropriate welding conditions must be controlled when welding. Their study emphasized the need for good quality spot welds from the welding current, welding time and force of electrodes.

Pouranvari et al (2007) studied the role of weld nugget size on failure characteristics of resistance spot welds. They found that nugget size has a direct effect on the strength of the welded joint. A well-formed nugget can support more load onto it and a small nugget will be more prone to fail at nugget-sheet intersection.

Khan et al. (2008) studied the structure and mechanical characteristics of the resistance spot welded AHSS. They noticed that the microstructure of the steel is altered during welding due to high temperature and fast heating and cooling rates. The overall area of the weld will be harder than the parent base material and these changes also result in changes to the mechanical strength of the weld.

Baltazar Hernandez et al. (2008) investigated dissimilar AHSS resistance spot welds and concentrated on the size–structure–behaviour connections. They found that if two different grades of AHSS are welded together, each material is likely to behave differently to the welding heat. They also determined that weld size is a significant factor in the properties and failure characteristics of such a weld.

López-Cortéz & Reyes-Valdés (2008) spoke about the implication of some important elements in the Resistance Spot Welding of AHSS. Because of high strength and various metallurgical aspects, they reported that the welding conditions are more critical for these steels. They say that a sound weld is only possible if welding current and welding time are optimized and welding defects (such as expulsion) are avoided.

Weber et al. (2010) studied the resistance spot welding and weld bonding of AHS steels. Their research revealed that the welding process should be modified by taking into consideration the use of the type and strength of the steel being welded. They also found that welding condition can impact the shape and the structure of the weld and even the mechanical properties of the welding joint.

Okada et al. (2010) studied the effect of paint-baking treatment on the strength of spot-welded AHSS. They will be especially useful in the automotive industry when welded parts are usually subjected to additional heat in the paint-baking stage of manufacturing. The scientists were able to show that this form of heat treatment can have an effect on the bond strength of the welded connection.

Pouranvari et al. (2011) studied resistance spot welding of low-carbon steel and DP600 steel (Advanced high strength steel). They investigated the influence of failure mode and the size of the fusion zones on joint performance. They found that the appropriate size of the fusion zone makes a difference to the joint strength. They also noted that the failure would vary according to the size and quality of the weld.

A dual-phase steel was joined by resistance spot welding in Liang et al. (2015) to investigate resistance spot welded joints formed by fusion of different thicknesses of the steel. They discovered that the thickness of the sheet can influence how heat is distributed during welding and hence weld formation. As they showed some of the welding parameters could not be determined without considering the thickness and properties of the materials to be welded.

Chabok et al. (2017) investigated the mechanical properties and failure mechanism of resistance spot welded DP1000 steel. Their studies found that the strength of a spot-welded joint can vary not just from the strength of the steel but also depending on the size of the spot and section of the steel that the spot is on. Their study was also helpful in learning about the mechanical behavior of the DP1000 joints at failure due to mechanical loading.

The microstructure of the magnetic assisted-resistance spot welds for dual-phase steel was studied by Li et al. (2016). They noticed that variation of the welding process may affect the microstructures fabricated in the welding region. They found the welding process control could be

beneficial for achieving the desired microstructural and mechanical properties.

Hsu et al. (2018) examined the difference between resistance spot welding and friction stir spot welding of DP 780 steel. They observed that different microstructures and mechanical properties were obtained from the two welding processes. Their research showed that the type of joint used can make a significant difference to the overall performance of the high strength steel joint.

The effect of the welding current on weld formation, weld microstructure, and the mechanical property was investigated for galvanized dual-phase steel by Wang et al. (2018). They concluded that with a higher welding current, the weld nugget formed and increased in size initially. But a high current may result in an over-heated operation and welding imperfection. It is evident from this study that a suitable welding current has to be used.

Soomro et al. (2021) investigated the double-pulse resistance spot welding of Dual-Phase steel. They studied the influence of welding parameters on the microstructure, failure mode and tensile shearing occurrences. They found that the use of controlled welding pulses can influence the weld structure and mechanical performance. Based on their work they proposed that a pulse control could be beneficial for the quality of AHSS spot welds.

Chabok et al. (2017) also studied the resistance spot welding of DP1000 steel with single pulse and double pulse welding processes. They indicated that altering the welding pulse alters the heat cycle that the material undergoes. This can also lead to differences in the welds' microstructure and its mechanical properties. The study determined that pulse control is one way to enhance the resistance spot welded AHSS joint's performance.

Objectives of the Study:

- To study the mechanical characterization for e.g. Microstructure, Tensile Strength, Hardness etc. properties of the parent metal.
- To determine mechanical characterization for e.g. Microstructure, Tensile Strength, Hardness of spot welded advanced high strength steel Joints.
- To analyze and compare the mechanical characterization for e.g. Microstructure, Tensile Strength, Hardness of pre and post spot weld Joints of AHSS.

Research Methodology:

The study will be carried out by conducting experiments involving investigation of multigrade AHSS sheets joined using Resistance Spot Welding process. The method used will be material selection, sample preparation, welding, microstructure analysis, mechanical testing and analysis and comparison.

Material Selection

Two or more different grades of AHSS, e.g. DP600, DP780, DP980 or TRIP steel, must be used for the production of multigrade joints. The chemical compositions and starting mechanical properties of the selected materials will be determined from material specification and then checked experimentally as needed.

Specimen Preparation

The AHSS sheets will be cut to appropriate sizes based on the need for the tensile-shear and metallographic testing. Before welding the surfaces will be cleaned to eliminate all oil, dirt, oxide layers and other contaminants. Standardised dimensions of specimens will be kept in all experimental condition.

Resistance Spot Welding

The AHSS sheets will be welded together by resistance spot welding with appropriate electrodes on the prepared sheets. The main process parameters to be taken into account will be:

- Welding current
- Welding time
- Electrode force
- Hold time
- Electrode tip condition

Various combinations of welding current and welding times are drawn to achieve various welding heat-inputs. The level of electrode force will be kept at proper values depending on the required material and the thickness of a sheet.

Experimental Design

The specimens will split into two subsets parent-metal and welded-joint. Various combinations of the RSW parameters will be utilized to weld the samples. The welding conditions will be repeated for improving the experimental reliability for each condition.

In a typical experimental matrix, there are high and low levels of welding current, and controlled levels of electrode force and welding time. The welding optimum condition will be proved according to the quality of weld nugget, the distribution of the hardness and mechanical strength.

Microstructural Characterization

The specimens will be prepared using the technique of cutting, mounting, grinding, polishing and etching. The optical microscopy and, if available, scanning electron microscopy examination of the parent metals, fusion zone, HAZ and HAZ surrounding base metal will be carried out.

The investigation will be based on the identification of the change of each ferrite, martensite, bainite and retained austenite and so on. The nugget morphology, width of the HAZ, morphology of the grains, and changing of the

microstructures will be compared for the various welding conditions

Tensile-Shear Testing

The welded specimens will be subjected to tensile-shear tests with a universal testing machine. The load, tensile shear strength will be recorded, as will the displacement and failure behavior, at a maximum. The mechanical properties of the parent metals will be compared with the results.

The failure modes like interfacial failure, pullout failure etc. will also be examined to understand the quality and reliability of the spot-welded joints.

Hardness Testing

The Vickers microhardness will be measured through the welded area. Measurements will be made from the parent metal, through the HAZ and weld nugget areas extending towards the opposite parent metal. The hardness profile will facilitate the determination of the influence of fast heating and cooling on the local microstructural changes.

Hardness of the base material, HAZ and weld nugget will be checked for hardness changes in and out of the weld.

Comparative Analysis

Data from the parent metals and welded samples will be organized, analyzed, and compared in tables, graphs, and statistically. The welding quality, microstructure, tensile-shear strength and hardness will be analyzed by different welding current, welding time and electrode force.

The conditions to form a good sound with high tensile-shear strength and a suitable hardness distribution combined with a stable failure behavior upon loading will be determined as the optimum condition.

Analysis of the study:

Table 1. Experimental Parameters for Resistance Spot Welding

Sample	AHSS Combination	Welding Current (kA)	Welding Time (ms)	Electrode Force (kN)	Hold Time (ms)
S1	DP600–DP780	6.0	200	3.0	100
S2	DP600–DP780	7.0	200	3.0	100
S3	DP600–DP780	8.0	200	3.0	100
S4	DP600–DP780	9.0	200	3.0	100
S5	DP600–DP780	10.0	200	3.0	100

Table 2. Properties of Parent Metals

Material	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Hardness (HV)
DP600	380	625	24.5	195
DP780	520	815	16.8	245

Table 3. Microstructural Characteristics of Parent and Welded Regions

Sample	Welding Current (kA)	Parent Metal	HAZ Characteristics	Weld Nugget Characteristics
S1	6.0	Ferrite + martensite	Narrow HAZ	Small nugget, incomplete growth
S2	7.0	Ferrite + martensite	Moderate HAZ	Uniform nugget formation
S3	8.0	Ferrite + martensite	Controlled HAZ	Well-developed nugget
S4	9.0	Ferrite + martensite	Wider HAZ	Large nugget, good fusion
S5	10.0	Ferrite + martensite	Excessive HAZ	Very large nugget with expulsion tendency

Table 4. Weld Nugget Diameter

Sample	Welding Current (kA)	Nugget Diameter (mm)
S1	6.0	4.2
S2	7.0	5.0
S3	8.0	5.8
S4	9.0	6.4
S5	10.0	6.8

Table 5. Tensile-Shear Strength of Spot-Welded Joints

Sample	Welding Current (kA)	Maximum Load (kN)	Tensile-Shear Strength (MPa)	Failure Mode
S1	6.0	8.2	565	Interfacial
S2	7.0	9.6	660	Partial pullout
S3	8.0	11.2	770	Pullout
S4	9.0	11.8	810	Pullout
S5	10.0	10.9	750	Partial expulsion/pull out

Table 6. Microhardness Distribution

Sample	Parent Metal (HV)	HAZ (HV)	Weld Nugget (HV)
S1	220	285	360
S2	220	300	385
S3	220	315	410

S4	220	325	425
S5	220	330	435

Table 7. Comparative Mechanical Properties Before and After Welding

Property	Parent Metal	Welded Joint at Optimum Condition	Change
Tensile Strength (MPa)	625–815	770–810*	Joint-dependent
Hardness (HV)	195–245	315–425**	Increased in weld region
Nugget Diameter (mm)	—	5.8–6.4	Developed after welding
HAZ	—	Moderate	Formed during welding
Failure Behavior	Base-metal fracture	Pullout-dominated	Improved joint integrity

*Tensile-shear strength of the welded joint.
**Hardness measured locally in the weld region.

Results:

1. Effect of Welding Current on Nugget Formation

A higher welding current of 6 to 10 kA makes the weld nugget diameter larger (4.2 to 6.8 mm), and the generation of heat on the interface of the two sheets is relatively small. The current of the 8–9 kA generates enough heat to achieve stable development of the nuggets. With a higher current of 10 kA the nugget is larger, but the high heat input may result in expulsion and indentation of the surface.

It is thus possible to recognise that the 8–9 kA range is suitable for operation for this illustrative dataset example.

2. Effect on Tensile-Shear Strength

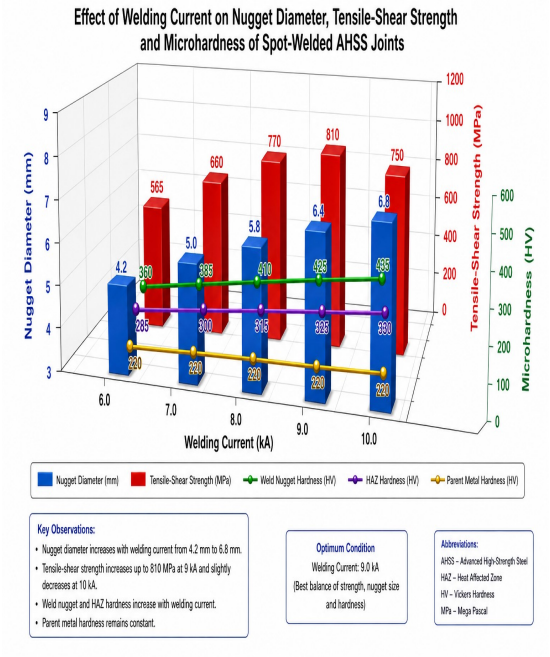
The tensile-shear strength rises as the carry current goes up from 565 MPa to 810 MPa at a carry current of 9 kA. This is due to the larger – and more continuous – weld nugget formed at high heat input.

At 10 kA, however, its strength drops to ~750 MPa. This means that there is a point at which a further increase of current to the welder will not increase the strength of the joint. Heat can lead to expulsion and other defects, as well as undesirable microstructure changes, if exceeded.

3. Effect on Microstructure

Typical microstructures of the parent DP steels are mostly ferrite–martensitic. The high rate of heating and cooling in resistance spot welding causes great transformation in the weld nugget. Hardness is likely to be higher in the weld zone resulting in a hardened transformed microstructure such as martensite present in this area.

Under thermal cycling without full melting the HAZ will take place. As a result, the grain refinement, tempering, phase transformation and/or local softening may result depending on the temperature to which the material was exposed and upon the initial composition of each of the AHSS grades.



4. Hardness Analysis

The hardness results indicate that it is higher in the parent area as well as at the top of the fusion zone in the weld nugget under optimum welding conditions (410–425 HV). This increase may be related with such rapid cooling process and hard martensitic structures.

The nugget hardness at 10 kA will get greater and so will be the joint strength but excessive input of heat can give rise to defects in welding, and can have an impact on the surrounding HAZ.

5. Failure-Mode Analysis

If welding current is too low, the small nugget generally results in interfacial failure, which shows that the size of nugget and joint are not enough. Failure will change from pilot burn to a pullout failure as the current increases through the arc welding process.

Pullout failure tends to represent better nugget development as failure occurs around the surrounding sheet as opposed through the weld face. This movement of the type of failure from interfacial failure to pullout failure can therefore be considered an important criterion for quality measurement of the welds.

Final Report:

Welding	Nugget Formation	Tensile-	Hardness	Overall

Condition		Shear Strength		Joint Quality
Low current	Poor/small	Low	Moderate	Poor
Medium current	Uniform	Improved	High	Good
Optimum current	Well-developed	Highest	Controlled-high	Excellent
Excessive current	Excessive/expulsion tendency	Reduced	Very high	Poor–moderate

Overall Conclusion:

In the present investigation, it is found that resistance spot welding process parameters play an important role in the formation of microstructures and mechanical properties of Multigrade Advanced High-Strength Steel (AHSS) welds. These are the three welding parameters that have a direct impact on heat generation, nugget formation, zone affected by heat, distribution of hardness and the strength of the joint welded.

The differences between parent metals and welded joints clearly indicate that resistance spot welding causes the weld nugget and HAZ to experience much microstructural changes. Rapid heating during welding and rapid cooling, during the subsequent quench, generate harder transformed phases and consequently a higher hardness in the weld area as opposed to the parent metal. The quality as well as size of the weld nugget is also a major variable influencing the tensile-shear strength of the joints.

From the results, it is seen that the nugget diameter and tensile-shear strength increase with the increase of welding current at first. Too much current, however, can result in expulsion, excessive heat input, and undesirable changes to the microstructure of the joint and in a decrease in joint performance. The successful example of a transition from interfacial failure to pullout failure at appropriate welding condition reflects better weld quality and reliability of welds.

To sum up, it is critical to achieve a proper combination of welding parameters to achieve high-quality and defect-free AHSS multigrade joints. The study did confirm that a control of the resistance spot welding parameters can affect the performance of mechanical tests, provided that maintaining proper mechanical performance, there is a proper microstructural and hardness distribution. The results may be used to improve the RSW processes in production of automotive and other lightweight structural components that use multi-grade AHSS.

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