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Evaluation of Weld Quality and Strength in Advanced High Strength Steel Sheets

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Abstract: Advanced High Strength Steels (AHSS) are common in the manufacturing industries especially in automotive industry owing to their high strength- weight ratio and increased mechanical properties. The welding of the AHSS sheets is very critical in the aspect of determining the structural integrity and the durability of the components made. Nevertheless, the welding processes can have an effect on the microstructure and mechanistic performance of these materials to a significant extent. The current paper assesses the quality of weld and mechanical strength of spot-welded AHSS sheets utilizing different welding parameters. Experimental analysis is done to study the relationship between the effects of current used in welding, tensile shear strength and failure behavior of weld nuggets in relation to welding time and electrode pressure. The integrity and performance of a weld is determined by metallurgical observation and mechanical test. The findings indicate that optimum welding settings are crucial in enhancing the strength of the weld and minimizing welding defects including expulsion and incomplete welds. The research also gives critical information on the ways to enhance the quality of welding and the dependable capability of AHSS joints in industrial use.
Keywords: Advanced High Strength Steel (AHSS); Spot Welding; Weld Nugget; Mechanical Strength; Weld Quality Evaluation; Welding Parameters

1. Introduction:

Advanced High Strength Steels (AHSS) have gained more significance in the current engineering and manufacturing practices because of their superior merger in quality of strength and superior formability coupled with superior crash performance. The steels are highly applied in automotive, transportation and structural industries where weight savings and accidents are among the very important demands. The need to have lightweight cars with better fuel efficiency as well as low emissions has prompted the manufacturers to make use of AHSS sheets in other structural parts.

AHSS materials have complicated microstructures consisting of martensite, bainite, ferrite, and retained austenite, which have better mechanical qualities than in other types of steel. Due to these properties, AHSS has increased tensile strength and increased energy absorption capacity but at a comparatively low weight. Consequently, greater usage of AHSS sheets in body structures and reinforcement parts as well as safety components is adopted by automotive manufacturers.

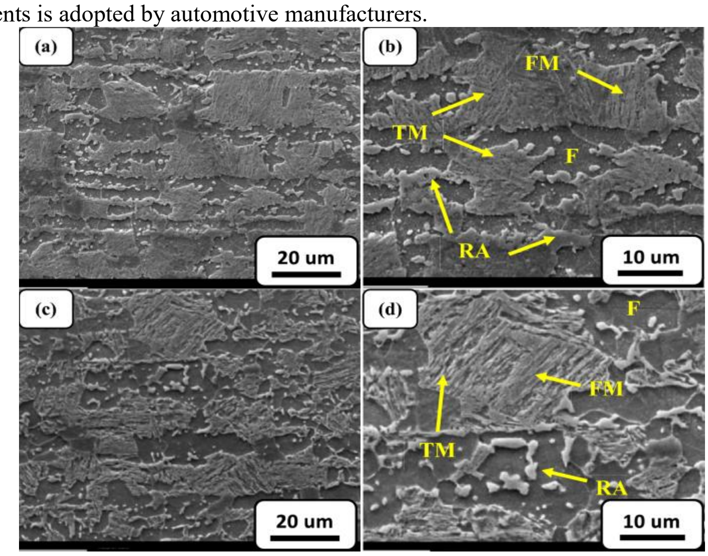

Fig. 1 weld quality in resistance spot welding of advanced high strength steels

- The figure demonstrates the general phenomena of the formation of the weld quality in the case of resistance spot welding (RSW) of advanced high strength steels (AHSS).
- It demonstrates the effects of such parameters of welding like welding current, electrode force, and welding time on developing the weld nugget.
- The diagram indicates that the heat is produced on the interface between two sheets of steel because of the resistance of electricity in the welding process.
- The molten and solidified metal is represented and hence forms a strong weld joint.
- The fact shows that electrode pressure and cooling are crucial in the control of quality of weld and any defects.
- Proper maximization of parameters: These assist in attaining sufficient nugget diameter, high joint strength and enhanced mechanical performance.
- The example underlines that the inadequate choice of parameters can lead to such defects of the welding as expulsion, cracks, or defective joints.

Welding of AHSS sheets is one important process in the production of sheet. The most popular method of joining employed in the automotive industry is the resistance spot welding (RSW) as it is very easy, fast, and economical. An average vehicle body might have thousands of spot welds in it and this makes the quality of the welds very essential in the amount of structural integrity of the vehicle. Nevertheless, welding AHSS materials is a challenging task due to the fact that its high strength and intricate microstructure have the potential to impact the heat transfer, development of weld nudges, as well as mechanical joint characteristics.

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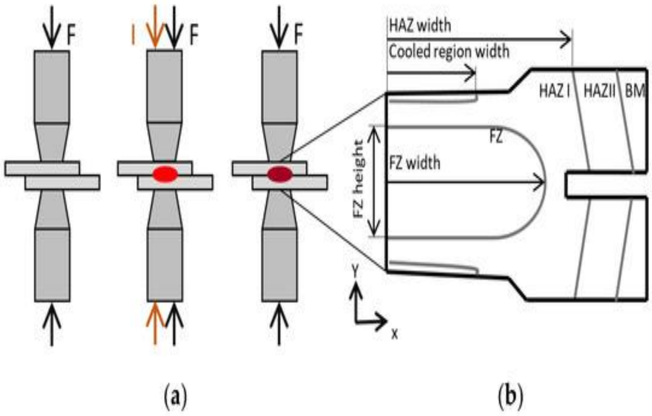

Fig. 2 spot welding of advanced high strength steel

Localized heating and rapid cooling during a welding process may cause tremendous distortion of the microstructure in the weld area and the heat-affect zone (HAZ). Such micro structural modifications can influence hardness, ductility as well as joint strength. Unsuitable welding conditions like too much welding current as well as too little welding time or improper pressure on electrode can attract defects like expulsion, welding cracks, porosity, or too small weld nuggets. These malfunctions can decrease the carrying capacity of the joint and decrease structural safety.Thus, the assessment of the quality of the weld and the mechanical performance should be considered to guarantee a stable work of the welded AHSS structures. The quality of spot-welded joints is usually estimated by parameters like diameter of weld nugget, tensile shear strength and failure mode. Avoidance of defects and the preservation of the desirable mechanical properties of the base material can be achieved by optimizing the welding Figure 1.A shows a successful optimization of welding parameters to increase the strength of the joints and reduce defects and minimization of the adverse effects on the desirable mechanical properties of the base material. In this regard, this research paper dwells on assessment of the quality of welds and mechanical strength of Advanced High Strength Steel sheets welded by the resistance spot methods. The study will examine the effects of critical welding parameters on the processes of the formation of weld, strength features, and joint functionality. Results of the proposed study will also help to enhance the welding operation and make an AHSS welded structure more reliable when used in industries.

2. Literature Review:

Advanced High Strength Steels (AHSS) has recently become a topic of extreme concern in the current manufacturing fats, specifically in the automobiles industry because of its superior strength-weight ratio, as well as its superior mechanical properties. Nevertheless, welding of AHSS sheet does not have a few technical challenges due to its complicated micro structure and high strength properties. Various researchers explored the behavior of resistance spot welding (RSW), quality of a weld and mechanical performance of joints of AHSS. The contribution of some of the past researchers in this area is examined as discussed in the following section.

Feizollahi et al. (2025) used a thorough investigation of influences on the quality of the welds through the resistance spot welding in advanced high-strength steels. This paper aimed at the effect of welding current, electrode force and welding time on the weld nugget formation and joint strength. According to their findings, the welding parameters can be controlled inadequately, which provokes the weld defects which may include expulsion, lack of sufficient fusion, and vulnerable joints. The authors have highlighted that to enhance the performance of weld joints in AHSS, there is a necessity to optimize welding parameters to generate high-weld strength and joint-reliable performance.Sun et al. (2024) examined tensile shear fatigue occurring on high-cycle and failure modes of resistance spot-welded AHSS sheets that had zinc coating. In their study they showed that the life of fatigue of welded joints is very strongly based on the size of weld nuggets and the microstructure of the weld zone. The distribution of heat in the course of blocking also finds out the presence of the zinc coating in determining the weld nugget and general fatigue gap of the joint. The research was that to improve fatigue performance it is vital to take time and select the appropriate parameter and also control the microstructure.

Noh et al. (2012) researched the nature of failure of spot-welded AHSS sheets and studied various types of failure that arise in the welded joints. The researchers compared tensile shear test and cross tension test to measure the structural performance of spot welds. They found out that the diameter of the weld nuggets and the thickness of the sheets are important factors that affect the failure mode. Bigger nuggets used to weld will result in a pull-out failure and therefore a stronger weld whereas the smaller ones usually result in interfacial fracture.

Dancette et al. (2010) used cross-tension and tensile- shear tests to extrapolate the mechanical behavior of resistance spot welded AHSS joints. The paper has emphasised that mechanical strength of welded joints is determined by the size of weld nugget, welding conditions as well as the structure of the heat-affected zone. It was also noted that the welding parameters can be different leading to drastic changes in the strength of the joints and their failure behavior (the authors).

The study by Li et al. (2015) was an experimental study concerning the weldability of ultra-high strength steel using the resistance spot welding. In their study, they showed that welding current and electrode pressure are very important determinants, which dictate weld nuggets formation and mechanical performance of welded joints. The authors have indicated that an increment in welding current tends to enhance nugget diameter and strength of the joint but too much of current can cause expulsion and decrease of the quality of the weld.

Jain et al. (2024) evaluated how the heat-affected zone of AHSS joints is influenced by the aspect of spot-welding. It was observed that thermal cycles which occur during the welding process have a major impact on the microstructure of the heat-affected zone. The greater the weld currents within the welding system the greater the martensitic structures and the more the hardness and possibly less ductility in the areas of the welded joint.

In an experimental and statistical optimization study carried out by Alzahougi et al. (2023), resistance spot welding of DP600 sheet steel was studied. The study involved statistical analysis of the best welding parameters to use in order to attain maximum joint strength and minimum defects. The authors of the research came to the conclusion that optimization of the processes is the key to the high quality of the welds and their stability in the performance.The study by Pouranvari and Marashi (2013) investigated the process of failure mode changes of resistance spot welded advanced high strength steels. They have found that weld nugget diameter is a determinant element in either the joint will experience interfacial fracture or pull-out mode failure. Higher sized nuggets tend to increase pull-out failure, which is regarded as an ideal failure mode of stronger joints.

Ma et al. (2008) researched microstructure and mechanical characteristics of resistance spot welded AHSS. The authors found that in the welding process, the microstructures in the weld zone were demonstrated to form due to rapid heating and cooling. Such modification makes it harder and stronger, though it can also be brittle in some parts of the joint.
Pouranvari (2011) was a critical assayer of the relationship that exists between the weld nugget size and the joint strength in resistance spot welding of advanced high strength steels. The study was able to establish that direct dependence exists on tensile shear strength and failure behavior on nugget diameter. It is imperative thus to maintain the right size of nuggets in order to attain optimum performance of the weld.
Nielsen et al. (2013) came up with methods of numerical modeling to examine the resistance spot welding of advanced high strength steels. Their model could be used to predict the temperature distribution, nugget formation and mechanical behavior as the welding process progressed. These types of simulation assist the researcher to learn the working mechanisms of welding and enhance the welding parameters to a greater extent.
Cho and Rhee (2003) studied the effect of the weld nugget size on the strength of the resistance spot welded joints. The findings established that the nugget diameter tends to increase joint strength and have a better bearing capacity with increased nugget diameter. Another important aspect that was internally brought out in the study is the need to ensure that the welding environment is properly set to attain optimum nugget formation.
Pouranvari and Marashi (2010) have studied various failure modes in the resistance spot welded dual-phase steels. In their research, they indicated that mechanism of failure is highly dependent on welding parameters and microstructure of the area of welding. Adequate management of welding parameters can be useful in attaining desirable failure modes as well as enhance joint reliability.
Senkaya et al. (2004) investigated the kinetics of weld nuggets at the resistance spot welding. Their studies had shown that heat production, electric resistance and current distribution are significant in regulating nugget development and quality of welding.
Babu et al., (2001) studied the resistance spot welding of steels in relation to its microstructural development. In their conclusion, it was found that high rates of thermal variations during welding produce substantial phase changes both in the weld area and heat affected zone which affect the mechanical characteristics of welded joints.
Gould (2007) came up with the use of weld lobe diagrams on advanced high strength steels to arrive at a range of the possible or acceptable range of the welding parameters to help create the acceptable weld. It is these diagrams which determine when safe operating parameters lie within the range and exclude the occurrence of defects like expulsion or lack of fusion.
On the whole, the analyzed literature points out that parameters of resistance spot welding, the weld nugget size, microstructural changes, and mechanism of failures are highly significant to the quality and mechanical strength of the weld made of AHSS sheets. In spite of the intensive research undertaken in the given field, more experimental research is still needy to assess an overall impact of the combination of parameters in welding process on the strength of the welds as well as on structural integrity. Thus, this study aims at experimentally examining the quality of weld and mechanical strength of the AHSS sheets at various welding parameters to determine the best weld parameters in enhancing the performance of the joints.

3. Objectives of the Study:

- To evaluate the weld quality of Advanced High Strength Steel (AHSS) sheets joined using the resistance spot welding process by analyzing weld nugget formation and surface characteristics.
- To analyze the effect of welding parameters such as welding current, welding time and electrode pressure on the mechanical strength of spot-welded AHSS joints.
- To determine the optimal welding conditions that provide maximum joint strength and improved weld quality for Advanced High Strength Steel sheets.

4. Research Methodology:

The research embraces the use of experimental research method to assess the quality and the mechanical strength of the welds with the Advanced High Strength Steel (AHSS) sheet under the resistance spot welding process. The study aims at examining how the parameters of welding affect the butt-welded joint strength and formation. The methodology will use material selection, welding experiment, mechanical testing as well as analyzing all obtained using metallography to determine the performance of the welded sample.
First, AHSS sheets of the same thickness are taken as the starting base material of the experiment. The sample is checked in the terms of a chemical composition and mechanical properties to make sure that the samples used in the experiment will be consistent. Standard specimen sizes are cut in the sheets to fit the resistance spot welding. Welding is done through the resistance spot welding machine in which the sheets are stacked and joined together under the electrode pressure and application of electrical current.
The welding current, welding time and electrode pressure are the important welding parameters that are adjusted during the welding operation to obtain varying welded samples. These parameters are regulated closely with the aim of examining the impact of such parameters on the formation of weld nuggets and their strength on a joint. Various experimental trials are done to achieve valid and similar results.Quality of the welds is tested after the welding process and done by some testing procedures. The weld formation is determined by the amount of nugget of the weld created measured. The tensile shear tests of the welded joints are done using a Testing machine called Universal test machine (UTM). The test defines the load carrying capacity of the welded joint and which failure mode of both samples.
Besides the mechanical test, a metallurgical test is conducted in order to monitor the microstructure of the weld area. The welded samples are cut, polished and observed under a microscope in order to observe the microstructure of the weld nugget, heat-affected zone (HAZ) and the base-metal. The observations are useful in the study of the structural transformation in the welding process.
Lastly, the experimental data are to be analyzed in order to find out the correlation between the welding settings and the indicators of welding quality including, nugget size, strength of the joint and the traits of failure. On this basis, best welding settings are known in order to ensure high composite welding strength and excellent joint performance levels in AHSS sheets. The stepwise experimental execution and the results were observed as is given in the following tables.

5. Analysis of the study:

Table 1: Material Properties of Advanced High Strength Steel (AHSS)

Property	Value	Unit
Material Type	Advanced High Strength Steel	—
Sheet Thickness	1.2	mm
Yield Strength	550	MPa
Ultimate Tensile Strength	980	MPa
Elongation	12	%
Density	7.85	g/cm³

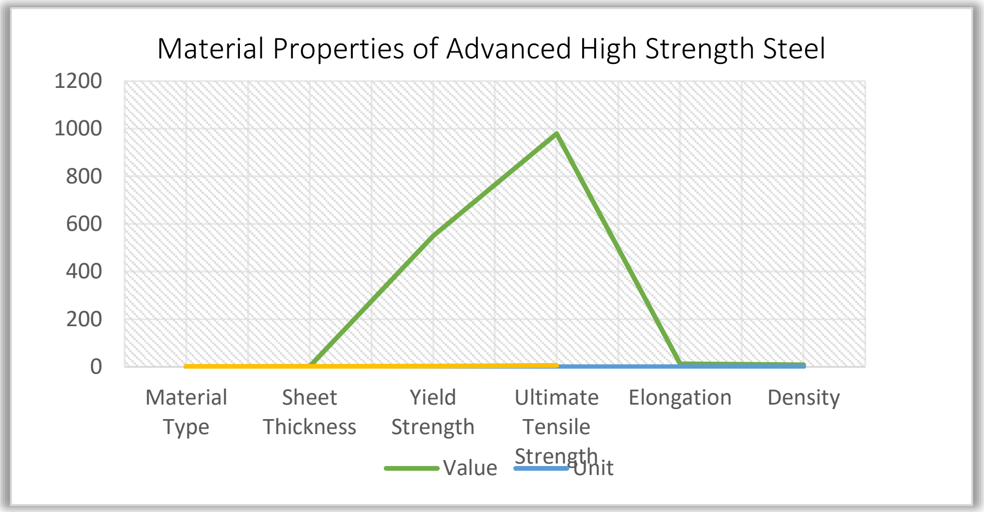

Table 2: Chemical Composition of AHSS Sheets

Element	Composition (%)
Carbon (C)	0.18
Manganese (Mn)	1.90
Silicon (Si)	0.30
Phosphorus (P)	0.02
Sulfur (S)	0.01
Iron (Fe)	Balance

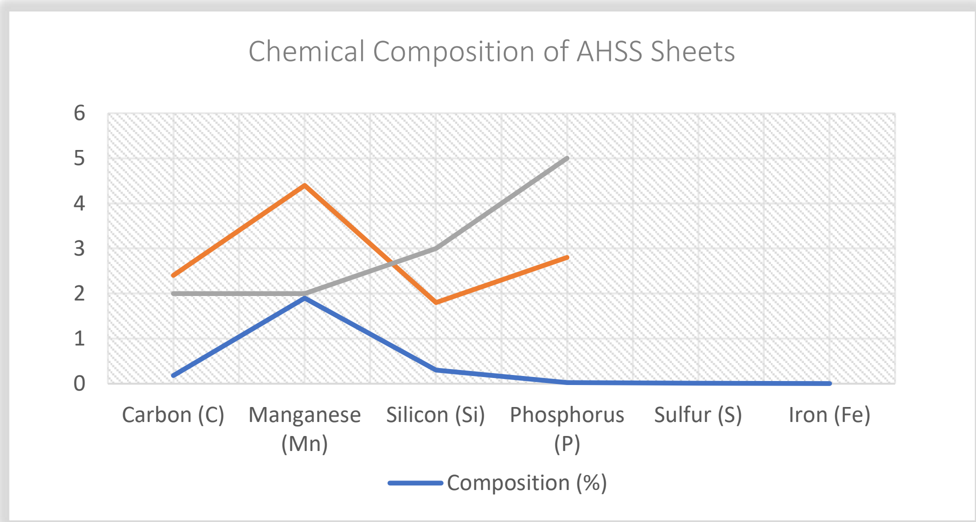

Table 3: Welding Parameters Used for Experimental Implementation

Sample No.	Welding Current (kA)	Welding Time (Cycles)	Electrode Pressure (kN)
S1	6	10	2.5
S2	7	12	2.5
S3	8	12	3.0
S4	9	14	3.0
S5	10	16	3.5

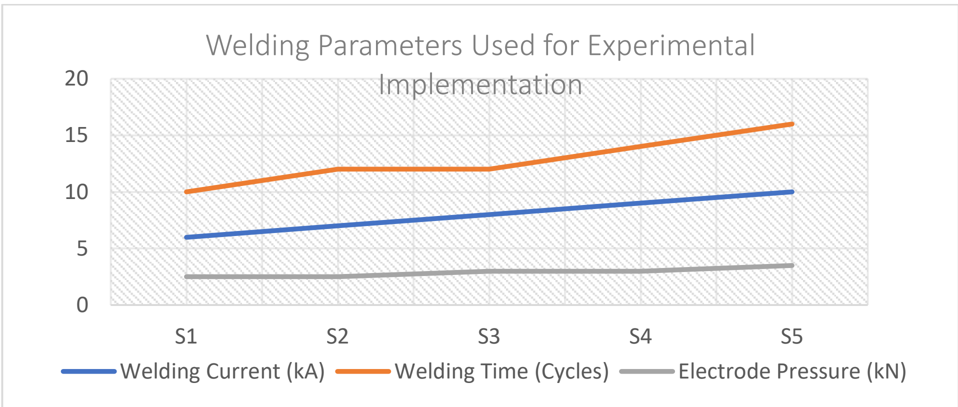

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Table 4: Weld Nugget Diameter Measurement

Sample No.	Nugget Diameter (mm)	Weld Quality Observation
S1	4.2	Incomplete fusion
S2	4.8	Acceptable
S3	5.4	Good
S4	5.9	Good
S5	6.1	Slight expulsion

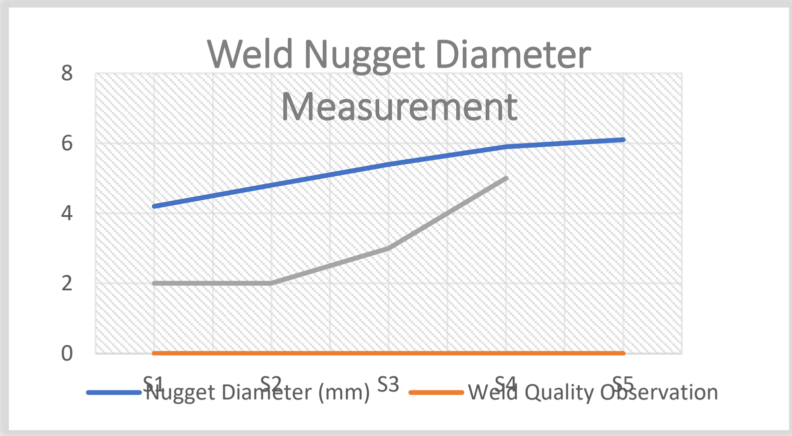

Table 5: Tensile Shear Strength of Welded Joints

Sample No.	Maximum Load (kN)	Failure Mode	Joint Strength Level
S1	3.8	Interfacial Failure	Low
S2	4.5	Partial Pull-out	Moderate
S3	5.2	Button Pull-out	High
S4	5.8	Button Pull-out	Very High
S5	5.6	Button Pull-out	High

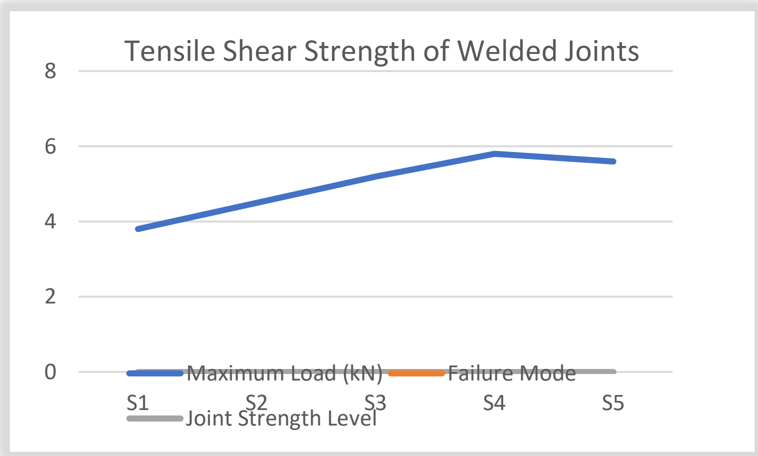

Table 6: Microstructural Observation of Weld Zone

Region	Observed Microstructure	Hardness Level
Base Metal	Ferrite + Martensite	Moderate
Heat Affected Zone	Martensitic Structure	High
Weld Nugget	Fine Martensitic Structure	Very High

Table 7: Summary of Optimized Welding Parameters

Parameter	Optimal Value
Welding Current	9 kA
Welding Time	14 Cycles
Electrode Pressure	3 kN
Average Nugget Diameter	5.9 mm
Maximum Tensile Strength	5.8 kN

6. Overall Conclusion:

The current paper was aimed at analyzing the quality and mechanical strength of welding□s with Advanced High Strength Steel (AHSS) sheets as a result of the resistance spot welding procedure. The experimental discussion has also revealed that the parameters of welding including current used in the welding, the time of the welding and also the electrode pressure are major determinants when it comes to the quality and strength of the joined pieces. These parameters should be controlled in order to come up with stable nuggets throughout the welding process as well as reduce welding errors.

The findings showed that the size of the weld nugget directly affects the performance of the joint in terms of mechanical performance. The larger and well-developed weld nuggets usually led to the increase in tensile shear strength and enhanced load carrying ability of the joining made by the welding process. Conversely, those with poor quality of welding current or lack of adequate welding time caused smaller nuggets and poor welting joints which can cause early failure during mechanical loading.
In the case of the images on microstructural observations, micro-structure and heat-affected zone experience dramatic structural changes on account of abrupt heating and cooling of the welding process. These changes lead to the differences in the hardness and mechanical strength within the region of welding. Martensitic structures form in the weld zone giving it hardness and strength, though some of them such as expulsion and brittleness can be caused by an overload of heat.
It was also revealed in the experimental results that an optimal set of welding parameters might lead to many benefits in the quality and performance of the weld joint. Optimal choice of parameters does not only increase the strength of the welds but also forms a consistent and reliable joint in the AHSS sheets.
On the whole, the research indicates that resistance spot welding can be a good method of joining Advanced High Strength Steel sheet in case welding parameters are selected properly. The results of this investigation can be helpful in the enhancement of welding techniques and better structural integrity of AHSS elements that are applied in the industrial and automotive sectors.

7. Future Scope of the Study

Even though the current paper conducted tests on the quality of welds and mechanical properties of sheets of Advanced High Strength Steel (AHSS) through resistance spot welding, there are several opportunities that are offered to explore further. The future studies can be dedicated to the further extension of the analysis to include other welding parameters like electrode geometry, electrode material and cooling conditions that can also affect the formation of a weld nugget and strength of the joint.
Additional researches can also focus on using the developed optimization method like artificial intelligence, machine learning, or statistical optimization algorithm to identify the best combination of welding parameters to enhance the quality of the welds. The techniques have the potential of predicting the performance of welding and lowering the time and cost of experiment.
Secondly, future studies can examine the fatigue behavior, strength of impact, and durability of Welded AHSS joints in various loading and environmental conditions in the long term. This would offer a better insight on the welded joint performance in actual industries especially in the automotive and structural industries.
The other opportunity of future investigations is microstructural characterization with the help of high-level analytical devices scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) to comprehend the changes of phases that take place in the weld and heat-influenced areas more deeply.
Lastly, various welding could be compared to understand the most effective and consistent welding option between the laser welding processes, the friction stir welding and the resistance spot welding in order to establish the most efficient process used to connect the Advanced High Strength Steel sheets. These studies would also help in the enhancement of production and the overall enhancement of the structural performance of the AHSS in the current engineering practice.

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