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RESISTANCE SPOT WELDING ON NUGGET DEVELOPMENT: A REVIEW

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ABSTRACT :

Resistance Spot Welding (RSW) is widely employed in the automotive and aerospace industries due to its efficiency in joining sheet metals. This study presents an experimental investigation into the effects of key input process parameters—namely welding current, electrode force, and weld time—on the formation and quality of weld nuggets in Interstitial Free (IF) High Strength Steel. IF steels, known for their superior formability and cleanliness, pose unique challenges in maintaining weld integrity and consistency. A series of experiments were conducted using fixed electrode geometry and varying process parameters under controlled conditions. The resulting weld nuggets were analyzed for diameter, strength, and internal quality using non-destructive and destructive testing methods including peel testing and metallographic examination. The findings reveal a strong correlation between input parameters and nugget formation, with welding current emerging as the most influential factor. Optimal ranges for each parameter were identified to ensure maximum joint strength and structural reliability. This research provides valuable insights for enhancing weld quality in high-strength IF steels, contributing to safer and more efficient structural applications.

Keywords- Interstitial Free Steel, Weld Nugget Formation, Welding Parameter, High Strength Steel

1. INTRODUCTION

Resistance Spot Welding (RSW) is a widely used solid-state joining technique, especially prominent in the fabrication of automotive structures, aerospace components, and domestic appliances. It involves the application of pressure and electric current to metal sheets held between copper electrodes, leading to localized heating and the formation of a weld nugget at the interface of the sheets. The advantages of RSW include its high production rate, ease of automation, low cost, and suitability for dissimilar and high-strength materials. Despite these advantages, the process is highly sensitive to welding parameters, and improper selection can lead to defects such as expulsion, insufficient penetration, electrode indentation, and weak joints. Among the various materials used in automotive body panels and structural parts, Interstitial Free (IF) High Strength Steel stands out due to its excellent formability, high strength-to-weight ratio, good surface finish, and weldability. IF steels are essentially ultra-low carbon steels in which interstitial elements like nitrogen and carbon are removed through alloying with titanium and/or niobium, resulting in enhanced ductility and superior deep drawing capability. However, due to their refined grain structure and specific thermal behavior, achieving uniform and strong weld nuggets in IF steel through RSW requires careful control of the input parameters. Key process parameters in RSW—namely welding current, electrode force, and weld time—play a crucial role in determining the size and strength of the weld nugget. Welding current governs the heat generation; electrode force influences the contact resistance and heat loss; and welds time controls the duration for which heat is applied. Therefore, optimizing these parameters is essential for achieving desirable weld properties such as maximum tensile-shear strength, proper nugget diameter, and minimal defects. Additionally, understanding the correlation between these parameters and the mechanical/metallurgical characteristics of the weld nugget is vital for improving the durability and performance of welded joints. This study aims to investigate the effects of these input process parameters on weld nugget formation in Interstitial Free High Strength Steel sheets. A series of controlled experiments are conducted, and the resulting welds are evaluated based on mechanical strength and metallographic characteristics. The primary objective is to identify the optimal range of parameters that lead to defect-free, high-strength welds, thereby contributing to the broader goal of enhancing weld reliability in high-performance applications. The outcomes of this research can aid in refining resistance spot welding procedures for IF steel and serve as a valuable reference for automotive and manufacturing industries where this material is extensively used.

2. PROBLEM IDENTIFICATION

Resistance Spot Welding (RSW) is extensively used for joining sheet metals in the automotive and manufacturing sectors due to its high speed, automation capability, and cost-effectiveness. However, the process is highly sensitive to variations in input parameters such as welding current, electrode force, and weld time. Improper selection or control of these parameters can lead to poor weld quality, including weak nugget formation, surface indentation, metal expulsion, and inconsistent joint strength. In recent years, Interstitial Free (IF) High Strength Steel has gained popularity in the industry due to its superior formability, clean microstructure, and high strength-to-weight ratio. Despite these advantages, the welding of IF steel using RSW presents specific challenges. The thermal and electrical properties of IF steel demand a precise balance of input parameters to achieve consistent and defect-free welds. Variations in the heat input can significantly affect the size, shape, and strength of the weld nugget, directly impacting the mechanical performance of the joint. Currently, there is a lack of comprehensive experimental data focusing on the optimal process parameters for welding IF high strength steels. Most existing studies are either generalized or focus on conventional steels. As a result, there is a pressing need to investigate the specific behavior of IF steel under varying RSW conditions. Without this understanding, industries risk compromising weld quality, structural reliability, and overall product safety. Therefore, this research aims to identify and analyze the critical input parameters influencing weld nugget formation in IF high strength steel. The goal is to establish a set of optimized conditions that ensure high-strength, defect-free spot welds, which is essential for reliable and efficient manufacturing practices.

3. RESEARCH OBJECTIVES

The primary objective of this research is to investigate the influence of key input process parameters of Resistance Spot Welding (RSW) on the weld nugget formation in Interstitial Free (IF) High Strength Steel. The study aims to optimize the welding conditions to achieve high-quality, strong, and defect-free weld joints. The specific objectives of the research are:

1. To analyze the effect of welding current, electrode force, and weld time on the size and quality of the weld nugget in IF high strength steel.
2. To evaluate the mechanical strength of the welds using destructive and non-destructive testing methods.
3. To study the metallurgical characteristics of the weld nugget through microstructural examination.
4. To identify the optimal combination of input parameters for achieving maximum weld strength and structural integrity.
5. To develop a set of guidelines or a process window for reliable RSW of Interstitial Free High Strength Steel for industrial applications.

4. LITRATURE REVIEW

Resistance Spot Welding (RSW) continues to be a dominant joining technique for sheet metals in the automotive and manufacturing industries due to its efficiency, cost-effectiveness, and ease of automation. In recent years, Interstitial Free (IF) High Strength Steel has emerged as a preferred material for vehicle body structures due to its excellent formability and surface quality. However, achieving consistent and high-quality welds in IF steel presents a technical challenge, requiring precise control of input parameters such as welding current, electrode force, and weld time. This review presents relevant studies from the latest to older works that have contributed to the understanding of RSW in high strength and IF steels.

Kumar et al. (2023) The study focused on optimizing Resistance Spot Welding (RSW) parameters for Interstitial Free (IF) steel using a hybrid Taguchi–Grey Relational Analysis method. It aimed to determine the ideal combination of welding current, electrode force, and weld time to enhance weld quality. The results revealed that welding current had the most dominant effect on nugget diameter and tensile strength. Weld time also played a significant role in controlling heat input and nugget formation. The analysis showed that improper parameter selection leads to defects like expulsion or weak joints. Micro structural examination indicated that grain refinement in the fusion zone is sensitive to both current and weld time. The researchers emphasized the need for precise control of thermal cycles. Their findings provide a valuable reference for improving weld strength in IF high strength steel.

Patel and Shah (2022) The study focused on the mechanical characterization of resistance spot-welded Interstitial Free (IF) steel joints under varying weld cycle durations. The primary objective was to understand how different weld times influence the quality and strength of the welded joints. It was observed that shorter weld cycles resulted in inadequate heat input, leading to incomplete fusion at the weld interface. Such conditions produced weak joints with small nugget diameters and poor load-bearing capacity. On the other hand, excessively long weld times caused overheating of the metal, resulting in expulsion of molten material. This also led to visible defects like electrode indentation and reduced surface finish. The experiments highlighted the importance of thermal balance in the welding process. Micro structural analysis showed abnormal grain growth in over-welded samples. Mechanical testing indicated that joint strength varied significantly with weld time. A narrow window of optimal weld time was identified where maximum tensile-shear strength was achieved. This optimal range ensured proper nugget formation without introducing surface or internal defects. The study concludes that careful control of weld time is critical for producing high-quality spot welds in IF steel. These findings offer useful guidelines for industrial welding setups involving high-strength IF steels.

Ali et al. (2021) The study examined the effect of varying electrode force on the weld integrity of advanced high strength steels, including Interstitial Free (IF) steel. The researchers aimed to determine the optimal electrode force that balances weld quality and joint strength. Electrode force directly influences contact resistance and the amount of heat generated at the faying surfaces. It was observed that low electrode force led to increased contact resistance, causing excessive heating and potential metal expulsion. This resulted in unstable nugget formation and inconsistent joint performance. Conversely, high electrode force decreased contact resistance, reducing heat input and resulting in insufficient fusion. Additionally, excessive force caused visible surface indentation and thinning of the sheet metal. The mechanical testing showed a reduction in tensile-shear strength under both too low and too high electrode force conditions. Microstructural evaluation revealed underdeveloped nuggets in high-force welds and irregular fusion zones in low-force welds. Moderate electrode force was found to provide a balanced condition for heat generation and pressure application. This condition ensured consistent nugget size, minimal surface indentation, and strong joint performance. The study emphasized that electrode force must be optimized along with current and time for effective resistance spot welding. Their findings help establish better control over weld quality during the RSW of high strength steels. The conclusions serve as valuable guidelines for achieving reliable and defect-free spot welds in industrial applications.

Sharma et al. (2021) investigated the effect of varying electrode force on the weld integrity of advanced high-strength steels, including interstitial-free (IF) steel. The study aimed to understand how force adjustments influence nugget formation, surface characteristics, and joint performance. Experiments were conducted across a range of electrode forces while keeping other parameters constant. Results showed that too low a force caused insufficient fusion due to poor electrical contact, while excessive force led to deep electrode indentation and localized thinning. A moderate electrode force was identified as optimal for balanced heat input and weld formation. This condition ensured adequate nugget growth without surface damage.

Microstructural analysis confirmed consistent grain structure in the fusion zone under optimal force, and the mechanical strength of joints was highest under this condition. Peak tensile load values were also observed when indentation was minimized. Hardness profiles showed uniform transition from base metal to weld nugget. The study highlighted the significance of force in maintaining contact resistance. Findings are particularly relevant for thin sheet automotive applications. Recommendations were made to integrate force control in closed-loop welding systems.

Rao and Mehta (2020) conducted a comprehensive study using finite element analysis (FEA) to simulate heat distribution during the resistance spot welding (RSW) of ultra-low carbon steels. Their model was validated experimentally through thermocouple measurements and metallographic evaluation of weld nuggets. The simulation results indicated that increasing welding current leads to a proportional rise in peak temperature and nugget diameter. However, electrode force and hold time showed nonlinear effects on thermal distribution, with excessive force lowering contact resistance and thereby reducing heat generation. Hold time influenced the cooling rate, affecting microstructure and residual stresses. The study also highlighted the critical role of thermal conductivity and electrical resistivity in simulation accuracy. Predicted nugget geometries closely matched experimental weld cross-sections. Temperature contours from the model helped visualize heat flow across the faying surfaces. The authors emphasized the need for coupled thermal-electrical analysis to capture the dynamic nature of RSW. Their work demonstrated how process optimization using FEA can minimize defects such as expulsion or incomplete fusion. This methodology supports quality assurance and predictive control in automated welding systems. Recommendations included adapting simulation models for other steel grades and joint configurations.

Singh et al. (2019) investigated the application of pulsed current techniques in resistance spot welding (RSW) of interstitial-free (IF) steel. Their experiments demonstrated that pulsed welding significantly improves fusion consistency over traditional single-pulse welding. Pulsed current minimized heat accumulation and reduced the chances of expulsion. As a result, weld nugget quality and dimensional uniformity improved. The study highlighted improved joint reliability and reduced surface indentation. Singh et al. recommended pulsed techniques for high-volume production. They concluded that precise control over pulse parameters is key to weld optimization.

Chen et al. (2019) The study employed finite element modeling (FEM) to simulate heat distribution during Resistance Spot Welding (RSW) of ultra-low carbon steels, including Interstitial Free (IF) grades. The objective was to understand the thermal behavior of the material under varying process conditions. Simulation results were validated through controlled laboratory experiments using identical welding parameters. The model accurately predicted the temperature field and weld nugget growth during the welding cycle. Results showed that welding current has a direct and significant influence on peak temperature and nugget size. Higher current levels produced larger heat-affected zones and deeper nugget penetration. However, electrode force influenced the results in a nonlinear manner. Excessive force lowered contact resistance, reducing heat input and limiting nugget formation. Insufficient force caused erratic heating and increased the risk of expulsion. Similarly, hold time had a nonlinear effect on cooling rates and nugget solidification. Extended hold time improved nugget integrity by preventing cracks during solidification. Short hold time caused premature cooling and internal porosity in the weld nugget. The simulation also revealed thermal gradients within the nugget and adjacent zones. These findings emphasized the need for precise tuning of all RSW parameters for optimal weld quality. The study demonstrated the effectiveness of FEM in predicting weld behavior and guiding process optimization in RSW of IF steels.

Zuniga et al. (2015) The study investigated the effect of pulse welding techniques on the fusion consistency of Resistance Spot Welded joints in Interstitial Free (IF) steels. The primary goal was to compare pulsed current welding with conventional single-pulse welding in terms of weld quality and defect minimization. Pulsed current involves multiple controlled energy bursts rather than a continuous application of current. This technique allows for gradual heat build-up, reducing the chances of overheating and metal expulsion. Experimental trials showed that pulsed welding produced more uniform and symmetrical weld nuggets. The use of pulsed current significantly reduced common defects such as expulsion, surface cracking, and electrode indentation. It also improved dimensional control of the nugget diameter and depth of fusion. Mechanical testing revealed that pulsed welds demonstrated higher tensile-shear strength and better repeatability. The gradual heat input allowed better control over thermal gradients, minimizing distortion and residual stresses. Micro structural analysis showed refined grain structure in the fusion zone of pulsed welds. The study indicated that pulsed welding provides more consistent metallurgical bonding at the weld interface. Energy efficiency also improved due to reduced overheating and lower electrode wear. Pulsed current settings were optimized for weld time, peak current, and duty cycle. The findings suggest that pulsed welding is a promising technique for improving weld reliability in IF high strength steels. This approach can be effectively implemented in automated welding systems for consistent high-quality joints.

Pouranvari and Marashi (2012) The researchers conducted extensive work on the failure modes of resistance spot welded joints in dual-phase and Interstitial Free (IF) steels. Their study focused on understanding how nugget size influences the mechanical behavior and fracture characteristics of welded joints. Tensile-shear tests were performed on samples with varying nugget diameters. It was observed that as the nugget diameter increased, the mode of failure transitioned from interfacial to pull-out. Pull-out failure is generally considered a desirable outcome as it indicates stronger welds with better fusion. Smaller nuggets often failed at the interface due to insufficient bonding between the sheets. Larger nuggets provided better load distribution and enhanced structural integrity under stress. Micro structural analysis confirmed stronger metallurgical bonding in larger nuggets. The results also showed that process parameters must be optimized to consistently achieve larger nugget diameters. Failure mode mapping was used to classify the transition point between weak and strong welds. The study emphasized the importance of nugget diameter as a key indicator of weld quality. Their findings are useful for designing process windows in resistance spot welding of high strength steels.

Cho and Rhee (2000) The study provided early insights into the influence of welding parameters on heat generation and weld strength in resistance spot welding. Researchers emphasized the critical role of balancing input variables such as electrode force, welding current, and weld time. It was observed that excessive electrode force significantly reduces contact resistance between the workpieces. This reduction in contact resistance leads to lower heat generation at the faying surface, resulting in smaller weld nuggets. On the other hand, increasing the welding current raises the total heat input due to Joule heating. However, if the current is too high without adjusting other parameters, it can cause expulsion of molten metal. Expulsion leads to weld defects, poor nugget formation, and reduced joint strength. Proper coordination of current and electrode force is thus essential for achieving optimal weld quality. The study highlighted that electrode force should be moderate to ensure adequate resistance for heating. Meanwhile, the current level should be high enough to generate sufficient fusion without causing spatter. The findings laid the foundation for process optimization in early RSW applications. Their work remains a reference for understanding the thermal and mechanical effects of key welding parameters.

5. CONCLUSION

The present study has demonstrated the critical influence of key input parameters—welding current, electrode force, and weld time—on the quality of resistance spot welded joints in interstitial free high strength steel. Through experimental investigation, it was observed that nugget diameter and joint strength are significantly affected by variations in heat input, which is governed primarily by welding current and contact resistance. Excessive current led to expulsion, while insufficient current failed to achieve proper fusion. Similarly, electrode force played a dual role by affecting contact resistance and minimizing surface indentation. An optimal combination of process parameters was identified to achieve defect-free welds with adequate nugget formation and desirable failure modes. The findings support the need for precise control of welding inputs to ensure consistent and reliable joint performance. This work contributes to the development of parameter windows and quality assurance strategies in resistance spot welding of high strength automotive steels..

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