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Resistance Spot Welding of Advanced High-Strength Steels

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A B S T R A C T

Resistance spot welding (RSW) is a high-volume joining process used extensively in automotive body-in-white structures because it produces joints rapidly, requires no filler metal, and can be automated. The increasing use of interstitial-free (IF), high-strength low-alloy (HSLA), and advanced high-strength steels (AHSS) has made weld quality more dependent on the interaction between electrical and thermal process parameters, base-metal chemistry, sheet thickness, coating, weld-zone microstructure, and loading condition. This review integrates the uploaded studies on IF steel, single- and double-pulse welding, fatigue behaviour, and HSLA/AHSS welds. Particular attention is given to nugget formation, dynamic resistance, hardness distribution, phase transformation, tensile-shear and cross-tension performance, failure-mode transition, and cyclic durability. IF-steel studies show that nugget diameter and loading mode strongly influence load-bearing capacity, while zinc coatings and dissimilar sheet combinations modify heat generation and weld metallurgy. Double-pulse studies on DP steels demonstrate that a second current pulse can partially remelt or anneal the primary nugget and alter martensitic substructure; reported mechanical benefits depend on the steel grade and pulse schedule, and are not universal. HSLA studies show that the fusion-zone hardness and critical nugget size influence whether fracture occurs through the interface or by pullout. Fatigue papers directly concerned with RSW establish the importance of nugget diameter and material combination, whereas several other supplied fatigue papers concern laser welding, friction stir welding, or drilled-sheet specimens and are therefore used only as supporting evidence on fatigue mechanisms, not as direct RSW data. The combined evidence indicates that robust RSW qualification should consider weldability lobes, microstructure, hardness, defects, failure mode, and service loading rather than nugget size alone.

Keywords: *Resistance spot welding; advanced high-strength steel; interstitial-free steel; HSLA; dual-phase steel; single pulse; double pulse; weld nugget; microstructure; fatigue; failure mode.*

1. INTRODUCTION

Resistance spot welding is a resistance welding process in which two or more overlapping metal sheets are clamped between water-cooled copper-alloy electrodes and joined by heat generated from electrical resistance. The applied electrode force establishes electrical contact and maintains the joint during heating and solidification. The process is widely used in automotive manufacturing because it is fast, repeatable, compatible with robotic production, and does not require filler material. The supplied review by Williams and Parker describes the importance of current, weld time, electrode force, electrode geometry, machine characteristics, and weldability lobes in maintaining consistent nugget formation [1]. Podržaj and co-workers further explain that monitoring and control depend on measured electrical and mechanical signals, including current, voltage, resistance, and electrode displacement or force [2].

Automotive lightweighting has increased the use of steels that combine high strength with formability. IF steels are designed with very low carbon and nitrogen contents, commonly stabilised by titanium and/or niobium, and are valued for deep drawability and surface quality. HSLA steels use microalloying and controlled processing to obtain higher strength while retaining useful formability. AHSS grades such as dual-phase (DP) and transformation-induced plasticity (TRIP) steels contain more complex phase structures and alloying additions. Their weld response can differ significantly from that of conventional low-carbon steel because hard transformation products, particularly martensite and bainite, may form during the rapid cooling associated with RSW [3].

A resistance spot weld is commonly described in terms of three principal regions: the fusion zone (FZ), the heat-affected zone (HAZ), and the unaffected base metal (BM). The FZ is the molten region that solidifies to form the weld nugget. The HAZ does not melt but experiences a thermal cycle sufficient to alter grain size, phase distribution, hardness, and local strength. The weld perimeter and sheet-sheet interface are critical locations because geometric discontinuities, residual stresses, and hardness gradients can concentrate stress and initiate cracking.

The performance of an RSW joint cannot be judged solely from its static tensile-shear strength. In automotive structures, joints may experience peel, cross-tension, impact, vibration, and long-term cyclic loading. A joint with a high peak load can still exhibit undesirable interfacial fracture, limited deformation, or poor fatigue resistance. The distinction between interfacial failure and pullout failure is therefore important. Interfacial failure propagates through the weld nugget, whereas pullout failure involves the nugget being pulled from one sheet, usually with greater surrounding sheet deformation.

Pouranvari's study of similar and dissimilar HSLA/low-carbon steel welds highlights the relationship between fusion-zone size, hardness, failure mode, ductility, and absorbed energy [4].

This paper synthesises the uploaded research material in four connected areas: (i) RSW metallurgy and mechanical behaviour of IF steels; (ii) single- and double-pulse RSW and its effect on AHSS microstructure; (iii) fatigue performance and the limits of the supplied fatigue evidence; and (iv) RSW of HSLA and related AHSS grades. The purpose is to compare reported findings, identify process–structure–property relationships, and establish practical conclusions for weld development and quality assessment.

2. METHODOLOGY

The work was conducted as a structured literature review of the research papers supplied for this term paper. The uploaded reference document, "A Study of Robotics and its Emerging Applications," was used as a guide for the overall sequence: title and authors, abstract, keywords, introduction, methodology, topic-wise technical discussion, conclusion, and references. The subject matter and technical claims in the present paper are based on the supplied RSW and related materials papers rather than on the robotics reference.

The source papers were grouped according to their principal subject. IF-steel papers were examined for nugget formation, welding-current and time effects, dynamic contact resistance, hardness, tensile-shear strength, impact toughness, and dissimilar welding. Single-/double-pulse papers were examined for current scheduling, weld control, remelting, annealing, segregation, phase transformation, residual stress, and mechanical performance. Fatigue papers were screened to distinguish resistance spot welding from other joining or specimen-preparation processes. HSLA papers were examined for weld-zone microstructure, fusion-zone hardness, failure-mode transition, and comparisons with DP and TRIP grades.

For each study, the review considered the material combination and thickness, welding or processing method, principal variables, test method, and conclusions stated by the authors. Quantitative values are reported only where they are clearly stated in the supplied papers. Values from different studies are not treated as directly interchangeable because sheet thickness, coating, electrode geometry, machine type, current waveform, test configuration, and material grade vary. The review is comparative and does not claim to reproduce a new experiment or to calculate a unified optimum parameter set.

A limitation of the supplied collection is that not every paper labelled as a fatigue study investigates RSW. Two fatigue papers concern laser-welded steel joints, one concerns friction-stir-welded aluminium, and one studies fatigue of HSLA sheets after drilling. These are not presented as direct evidence for RSW fatigue performance. They are used selectively to explain general fatigue considerations or dissimilar-joint behaviour. The most directly relevant fatigue evidence comes from the RSW study on nugget diameter and steel-sheet combinations, together with fatigue-related RSW material supplied in the IF/HSLA collection.

3. FUNDAMENTALS OF RESISTANCE SPOT WELDING

3.1 Working principle and heat generation

The heat generated during resistance welding is commonly represented by Joule's law. For a simplified constant-current case, the heat input is expressed as $Q = I^2Rt$, where I is welding current, R is the effective electrical resistance, and t is current-on time. In a real RSW cycle, current and resistance vary with time, contact pressure, surface condition, temperature, coating behaviour, and changing contact area. A more representative expression is $Q = \int I(t)^2R(t)dt$. Only part of this generated heat contributes to nugget formation; heat is also conducted into the sheets and electrodes.

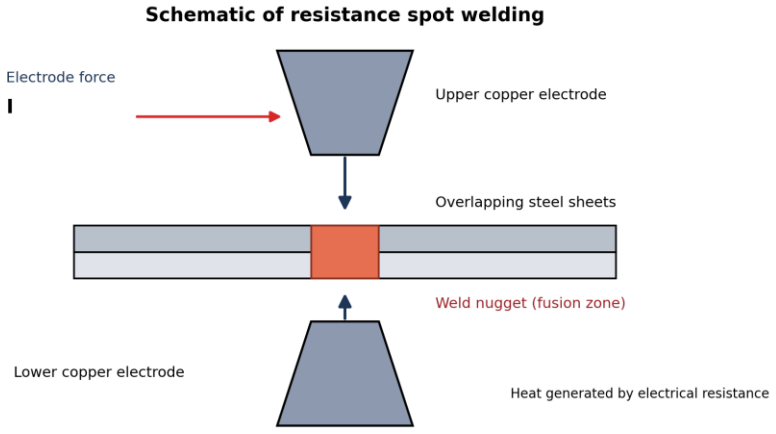


Fig. 1. Schematic arrangement of resistance spot welding and formation of a weld nugget.

The usual welding sequence includes squeeze time, weld time, hold time, and electrode release. During squeeze, the electrodes establish the required force. During weld time, current passes through the sheets and generates localised heat. During hold time, the electrodes maintain pressure while the

molten nugget solidifies. The electrodes are then released. Some schedules include preheat, cool, temper, or additional pulses. The sequence and timing of these stages influence the thermal cycle and the resulting microstructure.

3.2 Main process parameters

Table 1. Main process parameters in resistance spot welding

Parameter	Role in weld formation	Potential consequence if poorly selected
Welding current	Controls rate of Joule heating; strongly affects nugget growth.	Too low: undersized nugget or lack of fusion. Too high: expulsion, excessive indentation, or unstable weld growth.
Weld time	Determines duration of heat generation.	Too short: insufficient fusion. Too long: excessive heat input, wider HAZ, electrode wear, or expulsion.
Electrode force	Controls contact, resistance, and containment of molten metal.	Too low: unstable contact and expulsion. Too high: lower interface resistance and potentially insufficient heating.
Electrode tip geometry	Controls current density and contact area.	Wear or incorrect tip size changes nugget diameter and repeatability.
Coating / surface condition	Changes contact resistance and interfacial behaviour.	Can alter heat distribution, electrode life, and process window.
Current waveform / pulse schedule	Controls heat delivery over time.	Can influence nugget growth, segregation, tempering, residual stress, and phase transformation.

3.3 Weldability lobes and process control

A weldability lobe defines the range of current and time (or other selected parameters) that produces acceptable welds between the lower limit for adequate nugget formation and the upper limit associated with expulsion or other defects. Williams and Parker emphasise that welding-machine characteristics, electrode force, electrode diameter, and current waveform affect the available process window [1]. In production, the nominal setting should lie within a sufficiently wide lobe so that normal variation in material, fit-up, electrode wear, and machine output does not produce unacceptable welds.

Podržaj et al. review resistance spot welding control strategies and the signals used to infer process behaviour [2]. Dynamic resistance is particularly useful because its time history reflects changes in contact conditions, heating, softening, melting, and nugget development. However, a single signal should not be treated as a perfect measurement of nugget size. Reliable quality assurance combines process monitoring with destructive testing, metallography, mechanical testing, and periodic verification of electrode condition.

3.4 Microstructural zones and failure modes

The BM retains its original processed microstructure away from the weld. The HAZ experiences a range of peak temperatures and can be subdivided into subcritical, intercritical, fine-grained, and coarse-grained regions. In the FZ, melting and rapid solidification create a structure that may contain martensite, bainite, ferrite, or retained austenite depending on composition and cooling conditions. Water-cooled electrodes promote rapid heat extraction. The resulting hardness profile is therefore a function of both the steel chemistry and the local thermal history.

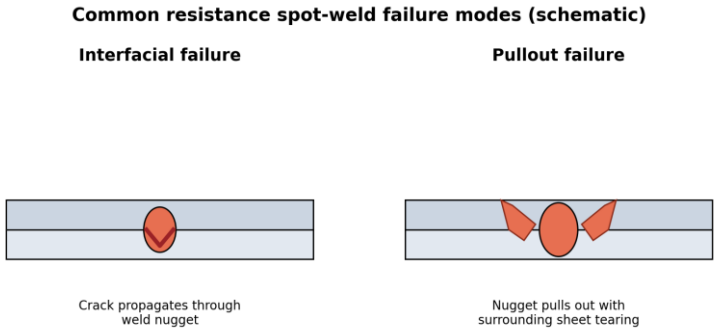


Fig. 2. Schematic comparison of interfacial and pullout failure in spot-welded sheets.

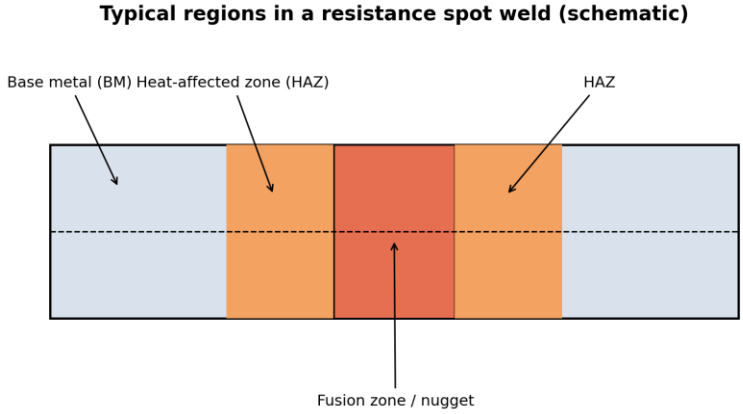


Fig. 3. Schematic cross-section showing the base metal, heat-affected zone and fusion zone.

Interfacial failure occurs when a crack propagates through the fusion zone, commonly producing a relatively flat fracture surface. Pullout failure occurs when the nugget is extracted from one sheet and the surrounding sheet tears or deforms. Pullout is generally associated with greater plastic deformation and energy absorption. The critical nugget diameter required for pullout is not universal: it depends on sheet thickness, FZ and HAZ strength, hardness gradients, material combination, and loading mode [4].

4. RESISTANCE SPOT WELDING OF INTERSTITIAL-FREE STEELS

4.1 Metallurgical characteristics of IF steel

Interstitial-free steel contains very low concentrations of carbon and nitrogen, with stabilising additions commonly used to bind residual interstitial atoms. This chemistry supports excellent deep drawability, formability, and surface quality. These characteristics make IF steel suitable for automotive body panels and other sheet components. Its relatively low strength and different electrical and thermal properties, however, mean that the welding schedule developed for a higher-strength steel cannot automatically be transferred to IF steel.

Beni, Atapour, Salmani and Ashiri investigated the metallurgy of thin zinc-coated IF steel sheets [5]. Their observations show that the HAZ contains ferrite grains elongated in the direction of heat transfer from the weld-pool boundary toward the BM. The nugget contains lath martensite, bainite, and different ferrite morphologies. Increasing heat input reduced the martensite fraction in the weld nugget, while measured nugget hardness remained higher than the HAZ and BM hardness. The study also reported both interfacial and pullout fracture, followed in some cases by tearing of the BM sheet.

The authors found that a nugget diameter of $4\sqrt{t}$, where t is sheet thickness, did not guarantee pullout fracture for the investigated zinc-coated IF steel. This is an important result because simple nugget-size rules are sometimes used as universal acceptance criteria. The study indicates that IF-steel weld qualification should include actual failure-mode assessment and should account for the metallurgy of the particular steel and coating [5].

4.2 Effect of current and weld time

Hayat, Demir, Acarer and Aslanlar studied the effect of weld current and weld time on spot-welded 7114 IF steel [6]. Their test matrix used welding currents of 3, 5, 7, and 9 kA and weld times from 5 to 30 cycles. Tensile-shear strength, tensile-peel strength, nugget diameter, and hardness were

evaluated. The reported trends show that increasing current and/or weld time increased nugget diameter and raised the load-bearing capacity and hardness of the weld and HAZ over the investigated range. The authors also constructed a weld lobe to describe the acceptable process window.

These results are consistent with the basic heat-generation relationship: increasing current or time generally raises the energy available for melting and nugget growth. The relationship is not indefinitely beneficial. Excessive heat can cause expulsion, indentation, excessive HAZ growth, or unfavourable microstructural changes. Thus, the practical objective is to find an adequate process window rather than to maximise current or weld time.

4.3 Nugget diameter and loading mode

Mukhopadhyay, Bhattacharya and Ray assessed the strength of spot-welded IF-steel sheets with different nugget diameters and loading configurations [7]. Nugget size was varied by changing welding current, and two IF steels with different chemistries were considered. Tensile-shear and pure-shear tests represented sliding modes, while cross-tension represented opening loading. Their results showed that load-bearing capacity increased with nugget size. For a given loading mode, the measured strength values were similar; sliding-mode strengths were higher than those measured under opening loading. The authors interpreted the differences using the Von Mises yield criterion.

The study also reported that the strength of the spot weld exceeded the strength of the BM in the examined configurations and maintained a relatively constant ratio to BM strength. The key engineering implication is that weld strength must be interpreted together with loading direction. A weld qualified only by tensile-shear testing may not exhibit the same capacity under cross-tension or peel loading.

4.4 Dissimilar IF-steel joints

Dissimilar welding introduces differences in electrical resistivity, thermal conductivity, melting behaviour, strength, and thickness. Hasanbasoglu and Kaçar investigated resistance spot welds between 7114 IF steel and AISI 304 austenitic stainless steel [8]. Their study examined the effect of peak current on weld morphology, microhardness, and tensile-shear load-bearing capacity. The reported optimum in their particular test configuration was a peak current of 9 kA, with electrode force maintained at 6×10^5 Pa and weld time at 17 cycles. Excessive grain growth in the IF-steel HAZ was identified as a principal cause of weakening.

Yaghoobi, Jamaati and Jamshidi Aval examined dissimilar IF–St52 low-carbon steel joints [9]. IF sheet thickness was fixed at 0.7 mm, while St52 thicknesses of 0.7 and 1.0 mm were considered. Welding currents of 6, 8, and 10 kA were applied at a constant electrode force of 5 kN. Increasing current increased nugget size and shifted the nugget toward the St52 side, attributed to the higher resistivity of St52. Increasing heat input changed the weld microstructure from predominantly martensitic toward mixed ferrite-bainite structures. The highest reported hardness was 673.3 HV for the thicker St52 configuration at 6 kA. Tensile-shear strength reached 2998.2 N for the 1.0 mm St52 configuration, while energy absorption decreased at 10 kA because of coarser microstructure.

The IF–St52 findings demonstrate that the best current depends on the required response: nugget growth and peak load may increase with current, but energy absorption can decline at high heat input. A process setting should therefore be selected using multiple performance measures rather than peak load alone.

4.5 Impact toughness and prestrain

Mukhopadhyay, Bhattacharya and Ray studied impact toughness of spot welds in IF steel sheets that were tested in the as-received condition and after 5, 10, and 15% prestrain [10]. The study reported that impact tensile toughness was higher than the corresponding quasi-static toughness measured using tensile-shear specimens. Within the investigated range, quasi-static toughness decreased as prestrain increased, whereas impact tensile toughness showed an opposite trend. The authors discussed the observations in relation to specimen configuration, test procedure, microstructure, substructure, hardness profiles, and post-failure examination.

This result cautions against assuming that quasi-static and impact performance change in the same way with prior deformation. It also reinforces the need to reproduce service-relevant loading conditions when evaluating spot-welded components.

4.6 Summary of IF-steel findings

Table 2. Summary of IF-steel findings

Study	Material / variable	Main finding relevant to RSW
Beni et al. [5]	Zinc-coated IF; heat input and weld metallurgy	Nugget contains martensite, bainite and ferrite; nugget harder than HAZ/BM; $4\sqrt{t}$ did not guarantee pullout.
Hayat et al. [6]	7114 IF; 3–9 kA and 5–30 cycles	Higher current/time increased nugget diameter, hardness and tensile load over tested range.

Study	Material / variable	Main finding relevant to RSW
Mukhopadhyay et al. [7]	IF sheets; nugget diameter and loading mode	Load capacity rose with nugget size; sliding strength exceeded opening strength.
Hasanbasoglu & Kaçar [8]	7114 IF / AISI 304	Study-specific optimum at 9 kA; excessive IF-side HAZ grain growth weakened the joint.
Yaghoobi et al. [9]	IF / St52; current and St52 thickness	Nugget shifted toward St52; higher current changed phases and increased peak load but reduced energy absorption at 10 kA.
Mukhopadhyay et al. [10]	Prestrained IF; impact vs quasi-static	Impact toughness exceeded quasi-static toughness; trends with prestrain differed.

4.7 Engineering interpretation

For IF steel, a sound welding procedure should establish current and time ranges using actual sheet thickness and coating, verify electrode force and tip condition, and monitor nugget growth. Metallographic checks should assess FZ shape, HAZ width, and evidence of expulsion or porosity. Hardness traverses can identify local hardening or softening, but should be interpreted with tensile-shear, peel, cross-tension, and where appropriate impact tests. Dissimilar combinations require particular attention to nugget offset and unequal sheet deformation.

5. SINGLE-PULSE AND DOUBLE-PULSE RESISTANCE SPOT WELDING

5.1 Current schedules and pulse terminology

A single-pulse schedule applies one principal current-on interval to form the nugget. A double-pulse schedule introduces a second current pulse after a controlled interval or cooling stage. The second pulse may reheat, partially remelt, temper, or anneal portions of the initial weld depending on its magnitude, duration, and timing. Multi-pulse schedules are not equivalent to simply increasing the duration of one pulse because the intervening cooling stage changes the temperature history and transformation path.

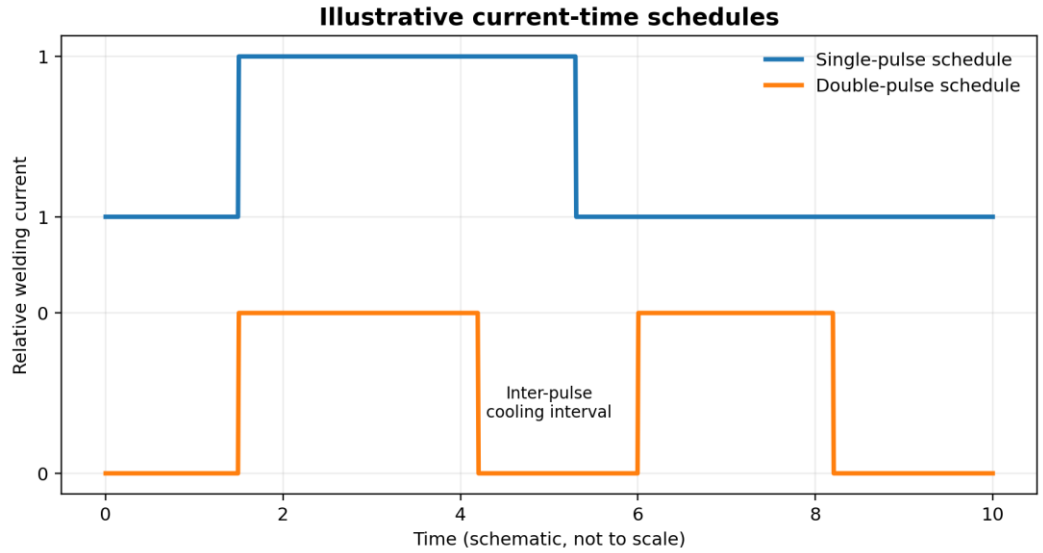


Fig. 4. Illustrative comparison of single- and double-pulse current schedules; the profiles are schematic and not measured data.

Williams and Parker describe a range of current schedules, including simple single impulses, multiple impulses, and upslope/downslope programmes [1]. Their review highlights that process control and machine characteristics are important because a nominal current and time do not fully describe the thermal history. Podržaj et al. similarly emphasise measurement-based control and the challenge of interpreting dynamic process signals [2].

5.2 Double-pulse microstructural mechanisms

Eftekharimilani, van der Aa, Hermans and Richardson examined the microstructural characterisation of double-pulse RSW in AHSS [11]. Their work reports that a second pulse can partially remelt the primary nugget and anneal material near the fusion boundary. The resulting changes affect segregation

and the microstructure of the weld region. The significance is that the second pulse modifies not only nugget dimensions but also local chemistry and phase development.

Zhong, Liao, Wang, Wu and Rong investigated double-pulse technology in DP600 steel [12]. They reported that the second pulse promoted the formation of acicular ferrite, retained austenite, and chromium carbides, and improved cross-tensile strength compared with their single-pulse condition. Their analysis related the acicular ferrite formation to the thermal history and its crystallographic relationship with surrounding martensite laths. The findings support the concept that a controlled second thermal cycle can change the fracture response by modifying the local microstructure.

5.3 DP1000: mechanical behaviour and failure mechanism

Chabok, van der Aa, de Hosson and Pei studied the mechanical behaviour and failure mechanism of RSW DP1000 [13]. Their work compared single- and double-pulse conditions and linked weld-zone microstructure to mechanical response. The double-pulse schedule was reported to enhance cross-tension strength compared with the single-pulse schedule in the investigated conditions. The second pulse subdivided the original fusion zone into an inner region with a columnar structure and an outer recrystallised region, referred to as the Rex-zone, with equiaxed prior-austenite grains.

The authors used orientation imaging microscopy to examine martensite in the Rex-zone and coarse-grained HAZ. The Rex-zone exhibited a lower fraction of high-angle grain boundaries and coarser Bain groups than the coarse-grained HAZ, while the coarse-grained HAZ contained finer Bain groups and a higher fraction of high-angle boundaries. The reported improvement in cross-tension behaviour was associated with changes in the weld-zone microstructure and reduced stress concentration through softening in the subcritical HAZ.

5.4 Pulse scheme, residual stress and the importance of parameter range

Chabok and co-workers subsequently examined the effect of pulse scheme on microstructural evolution, residual stress, and mechanical performance of DP1000-GI [14]. Their results show that the influence of double-pulse welding depends on current level. At low welding current, double-pulse welding decreased maximum cross-tension strength and mechanical energy absorption. Residual-stress mapping showed that compressive residual stress perpendicular to the pre-crack plane decreased or was released near the weld edge. The martensite in front of the pre-crack also showed a lower fraction of high-angle grain boundaries and coarser Bain groups in the double-pulse weld.

This result is important because it qualifies the general claim that double-pulse welding always improves joint performance. The DP1000 study [13] reported an improvement under its investigated schedule, while the DP1000-GI study [14] found lower performance at low current. The apparent difference is not necessarily contradictory: steel coating, pulse timing, current level, residual stress state, crack orientation, and test configuration all affect the result. A double pulse must therefore be optimised for the particular material and loading condition.

5.5 Comparative interpretation

Table 3. Reported effect of the second pulse in double-pulse RSW

Research	Steel / method	Reported effect of second pulse
Eftekharimilani et al. [11]	AHSS; microstructural analysis	Partial remelting and annealing near fusion boundary; altered segregation and weld microstructure.
Zhong et al. [12]	DP600	Acicular ferrite, retained austenite and chromium carbides; improved cross-tension strength in tested conditions.
Chabok et al. [13]	DP1000	Second pulse formed inner columnar region and outer Rex-zone; improved cross-tension strength in tested schedule.
Chabok et al. [14]	DP1000-GI	At low current, double pulse reduced cross-tension strength and energy absorption; residual-stress and martensitic features contributed.

5.6 Practical implications

Double-pulse schedules should be developed by controlling the first-pulse nugget, inter-pulse interval, second-pulse current and duration, and hold/cooling conditions. Metallography should establish whether the second pulse causes partial remelting, recrystallisation, tempering, or excessive grain growth. Hardness mapping and residual-stress measurements can help explain mechanical changes. Tensile-shear strength alone is insufficient when the design is sensitive to cross-tension or crack propagation. The best schedule is the one that produces the required combination of strength, ductility, energy absorption, and repeatability without expulsion or other defects.

6. FATIGUE BEHAVIOUR OF WELDED STEEL JOINTS

6.1 Why fatigue performance matters

Spot welds in vehicle structures are subjected to repeated loading caused by road inputs, vibration, acceleration, braking, body flexure, and local component deformation. Fatigue cracks may initiate at the weld perimeter, sheet-sheet interface, indentation, notch-like geometric features, or defects. The fatigue life is influenced by the applied load range, load ratio, sheet thickness, nugget diameter, material strength and ductility, weld geometry, residual stress, surface condition, and the number and arrangement of neighbouring welds.

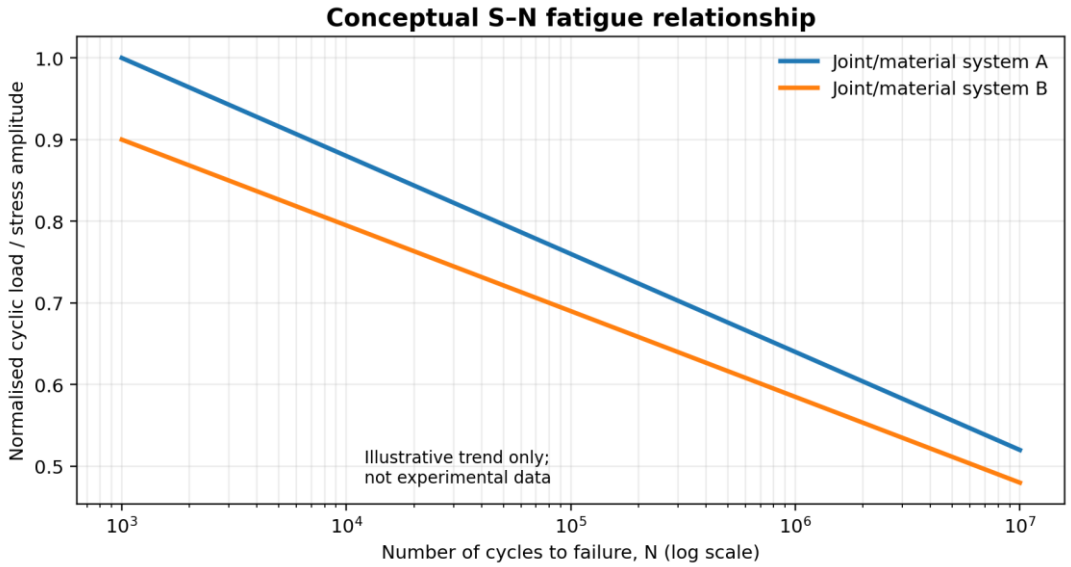


Fig. 5. Conceptual S–N relationship for fatigue; curves are illustrative and do not represent results from the cited papers.

Fatigue behaviour is often presented using S–N curves, which relate cyclic stress or load amplitude to the number of cycles to failure. In lap-shear spot-welded joints, nominal stress may not represent the highly localised stress field around the nugget. Therefore, comparisons should preserve the specimen geometry, loading mode, and test definition. A larger nugget can increase load-transfer area, but fatigue life is also affected by local bending and stress concentration.

6.2 Direct RSW fatigue evidence: effect of nugget diameter

Vural, Akkuş and Eryürek studied the effect of nugget diameter on fatigue strength of resistance spot-welded joints made from different steel sheets [15]. The study included galvanized steel and AISI 304 austenitic stainless steel combinations in lap-joint configurations. High-cycle fatigue tests were conducted and S–N curves were obtained. The galvanized-steel combination exhibited the highest fatigue limit, while the galvanized–AISI 304 combination showed the lowest fatigue limit among the investigated combinations. For the stainless-steel/galvanized-steel joint, the authors also examined nugget diameter and crack length after fatigue testing and evaluated crack-growth behaviour using the Paris–Erdogan relationship.

The study demonstrates that fatigue strength depends on material combination and nugget geometry. It also illustrates why a single fatigue limit cannot be transferred across dissimilar steel combinations. Electrode settings and nugget size should be qualified for the exact material pair and specimen geometry.

6.3 Fatigue studies using other joining processes: supporting evidence only

Several supplied papers provide useful information about fatigue in HSLA and DP steels but do not investigate RSW. Parkes et al. studied fiber-laser-welded similar and dissimilar HSLA/DP980 joints [16]. The fusion zone contained martensite, and an asymmetric hardness profile was observed in the dissimilar joint. The study reported high joint efficiency relative to HSLA base metal and showed that fatigue failure location varied with stress level: at high cyclic stress, failure occurred in the HSLA base metal, while at intermediate and lower levels failure occurred in the weld area, with sensitivity to weld concavity. These observations are relevant to the general influence of weld geometry and material mismatch, but the numerical fatigue results must not be attributed to RSW.

Cui et al. examined tensile and fatigue properties of single and multiple dissimilar laser-welded DP980/HSLA joints [17]. They found that fatigue performance depended on stress amplitude: DP980 performed better at high stress amplitude, while the more ductile HSLA performed better at low stress amplitude. Weld defects affected DP980 fatigue strength more negatively than HSLA. Since the process was fiber-laser welding, these findings are supporting evidence about dissimilar steel behaviour and defect sensitivity, not a direct comparison of spot-weld fatigue life.

Su et al. studied fatigue analyses and life predictions of laser-welded lap-shear specimens made from low-carbon and HSLA steels [18]. The study used quasi-static and fatigue testing and examined failure modes and fracture surfaces. Its relevance is methodological: fatigue life prediction should consider the actual joint geometry and failure mechanism. However, laser-welded lap joints have a different weld geometry and load path from RSW joints.

Policena et al. evaluated fatigue failure of HSLA sheets after conventional drilling and flow drilling [19]. The specimens were not welded. Their fractography identified ductile fracture associated with nucleation, growth, and coalescence of microvoids. This paper is not used to infer spot-weld fatigue life; it provides a separate example of cyclic failure in HSLA sheet and illustrates the value of post-failure fractography.

Infante et al. investigated dissimilar aluminium joints produced by friction stir welding [20]. Because both the material system and joining process differ from steel RSW, the paper is not used as direct evidence in the present RSW comparison. It is retained in the source screening record but excluded from quantitative conclusions.

6.4 Fatigue design implications for RSW

The available direct RSW fatigue paper supports the importance of nugget diameter and material combination [15]. Combined with the IF and HSLA mechanical studies, it is reasonable to identify several variables that should be controlled during fatigue qualification: nugget diameter and shape, weld indentation, expulsion, porosity or internal discontinuities, residual stress, HAZ softening or hardening, sheet thickness, and load direction. These are engineering synthesis points; the supplied papers do not provide one unified fatigue model for all IF, HSLA, and AHSS grades.

Fatigue testing should use representative joint geometry and loading. Where service loads are variable, testing should include the relevant load ratio and spectrum rather than relying only on a single constant-amplitude condition. Fracture surfaces should be inspected to identify whether failure initiated at the nugget edge, propagated through the FZ, or caused sheet tearing. For dissimilar joints, the weaker or more fatigue-sensitive sheet may govern the joint response at some stress levels, while the stronger sheet may dominate at others.

6.5 Evidence classification of the fatigue source set

Table 4. Evidence classification of the fatigue source set

Supplied paper	Process / specimen	How it is used here
Vural et al. [15]	Resistance spot-welded steel sheet lap joints	Direct RSW fatigue evidence; S–N behaviour and nugget/material effects.
Parkes et al. [16]	Fiber laser welded HSLA–DP980	Supporting comparison only; not RSW.
Cui et al. [17]	Single/multiple laser-welded DP980–HSLA	Supporting comparison only; not RSW.
Su et al. [18]	Laser-welded low-carbon/HSLA lap-shear	Supporting fatigue-analysis methodology only; not RSW.
Policena et al. [19]	Drilled HSLA sheet specimens	Not a welded joint; supporting HSLA fracture context only.
Infante et al. [20]	Friction-stir-welded aluminium	Different material and process; excluded from RSW conclusions.

7. RESISTANCE SPOT WELDING OF HSLA AND ADVANCED HIGH-STRENGTH STEELS

7.1 HSLA steel and its weldability

HSLA steels achieve increased strength through controlled composition and processing, often using microalloying additions and grain refinement. In the base-metal condition, HSLA may contain a ferritic matrix with fine carbides or other strengthening constituents. During RSW, the FZ and HAZ experience rapid thermal cycles. Depending on carbon equivalent, alloy content, cooling rate, and sheet thickness, the FZ may transform into martensite and/or bainite, increasing local hardness relative to the BM.

Khan, Kuntz, Biro and Zhou compared RSW of HSLA with AHSS grades 590R, DP600, DP780, and TRIP780 [3]. Their study describes the microstructure and mechanical properties of the weld zones and develops a relationship between steel chemistry and FZ hardness. The HSLA base metal had a ferritic structure with carbides and hardness around 150 HV in the reported material. The FZ hardness increased relative to the BM for all examined steels; the HSLA FZ was near 300 HV, while the examined AHSS grades generally exceeded 350 HV. These values are specific to the tested materials and schedules.

The authors explain that the HAZ contains subcritical, intercritical, fine-grained, and coarse-grained regions. The peak temperature and time above critical transformation temperatures influence the local structure. In the FZ, rapid solidification and cooling under water-cooled electrodes promote martensitic

or bainitic transformations, especially in steels with higher alloy content. This provides a metallurgical explanation for the higher FZ hardness in many AHSS grades.

7.2 Failure-mode transition in HSLA and low-carbon steel

Pouranvari investigated the transition from interfacial to pullout failure in similar and dissimilar RSW combinations of HSLA420 and low-carbon steel [4]. The study used 1.5 mm sheets and compared HSLA/HSLA, low-carbon/low-carbon, and HSLA/low-carbon combinations. Welding current was varied from 6 to 11.5 kA at a weld time of 0.2 s, with electrode force maintained at 4 kN. The study focused on tensile-shear testing and related failure mode to fusion-zone size and hardness.

The HSLA/HSLA combination exhibited the highest tendency toward interfacial failure, whereas the HSLA/low-carbon combination achieved pullout failure at a substantially smaller fusion-zone size. The reason is linked to differences in hardness and strength between the weld nugget and the surrounding sheet/HAZ. A harder fusion zone relative to the surrounding material can favour crack propagation through the nugget unless the nugget is sufficiently large to promote sheet tearing. The study also compares peak load, ductility, and energy absorption, emphasising that failure mode is important in addition to peak force.

The article notes that the commonly used $4\sqrt{t}$ nugget-size criterion does not always guarantee pullout in HSLA. It reviews models that relate critical weld size to sheet thickness, HAZ strength, FZ toughness, porosity, and hardness ratio. The practical conclusion is that the critical nugget size should be established for the actual steel grade and loading mode, not assumed from a universal rule.

7.3 Comparative AHSS microstructures

The Khan et al. comparison [3] provides a useful framework for interpreting the weldability of different AHSS families. DP steels consist of hard martensite islands in a softer ferrite matrix; increasing martensite fraction generally increases strength. TRIP steels contain retained austenite and bainite within a ferritic matrix, and the retained austenite can transform during deformation. Ferritic-bainitic 590R contains bainitic strengthening constituents and was developed to combine strength and formability. These base-metal structures respond differently to the RSW thermal cycle.

During RSW, the HAZ can undergo tempering, partial austenitisation, grain refinement, or grain coarsening. In DP and TRIP steels, the local transformation of ferrite and austenite can produce complex mixtures of martensite, ferrite, and bainite. In the FZ, the rapid cooling rate can produce a high fraction of hard transformation products. As a result, weld hardness may be substantially higher than BM hardness, and local brittle regions may influence cross-tension performance and failure mode.

7.4 Similar and dissimilar steel combinations

Dissimilar RSW is challenging because the two sheets may differ in thickness, resistivity, thermal conductivity, coating, strength, and hardenability. These differences can move the nugget toward one sheet, create asymmetric HAZ widths, and produce non-uniform hardness profiles. The IF–St52 results of Yaghoobi et al. [9] and HSLA–low-carbon results of Pouranvari [4] demonstrate that dissimilar joints may have different critical nugget-size requirements and failure paths from similar-material joints.

In the HSLA–low-carbon combination, the lower-strength sheet can deform and tear around the nugget more readily than the HSLA sheet. In an IF–St52 combination, the nugget position and local phase balance are affected by resistivity and sheet thickness differences. Therefore, welding schedules for dissimilar sheets should be designed around the actual pair rather than by averaging the properties of the two materials.

7.5 HSLA research summary

Table 5. Summary of HSLA/AHSS research

Study	Material / variables	Key result
Khan et al. [3]	HSLA, 590R, DP600, DP780, TRIP780	Compared weld microstructures and mechanical properties; AHSS FZ hardness generally exceeded HSLA.
Pouranvari [4]	HSLA420/LCS similar and dissimilar welds	HSLA/HSLA had greatest interfacial-failure tendency; HSLA/LCS pulled out at smaller FZ size.
Rivett-era HSLA study [21]	HSLA vs SAE 1008; electrode and welding parameters	Supplied historical study compares electrode size, force, current and time using tensile, cross-tension, impact and fatigue tests.

7.6 Practical recommendations for HSLA/AHSS weld development

A practical HSLA/AHSS weld-development programme should begin with material identification, including grade, thickness, coating, and available chemistry or carbon-equivalent information. Weldability lobes should then be developed for the actual material stack. The programme should monitor electrode force, current waveform, weld time, and electrode wear. Destructive verification should include nugget size, macrostructure, microhardness, tensile-shear, peel or cross-tension testing, and failure-mode classification. For high-strength steels, the target should be a robust failure mode and adequate energy absorption, not merely a minimum nugget diameter.

Where double-pulse schedules are considered, the first and second pulses should be varied systematically. The process should be assessed for partial remelting, local annealing, segregation, residual stress, and phase transformation. Fatigue testing should follow once static and metallographic acceptance criteria are established, because a schedule that improves one static loading mode may not improve all other loading modes.

8. INTEGRATED DISCUSSION

8.1 Process–structure–property relationship

Across the supplied literature, a consistent chain links process parameters to joint performance. Current, time, force, electrode geometry, coating, and pulse schedule determine the electrical and thermal history. The thermal history controls melting, solidification, grain growth, phase transformation, and residual stress. These structural changes establish the hardness distribution and local strength/toughness of the FZ and HAZ. Under mechanical loading, these properties interact with nugget geometry and joint configuration to determine peak load, deformation, energy absorption, failure mode, and fatigue life.

For IF steel, process settings that enlarge the nugget generally increase tensile load-bearing capacity, but the metallurgy and coating can prevent a simple size criterion from guaranteeing pullout [5–9]. For HSLA and AHSS, alloying and hardenability strongly influence FZ hardness and failure mode [3,4]. For double-pulse RSW, a second thermal cycle can alter the local weld structure and residual stress, but its effect can be positive or negative depending on schedule and material [11–14]. For fatigue, nugget diameter and material pairing are important, but the direct RSW fatigue evidence supplied is limited compared with the static and microstructural literature [15].

8.2 Why a single optimum parameter set is not appropriate

The uploaded studies use different steel grades, sheet thicknesses, coatings, electrodes, machines, current waveforms, weld times, electrode forces, and test configurations. For example, a current value that is appropriate for 1.6 mm galvannealed IF steel cannot be transferred directly to a 0.7 mm IF/1.0 mm St52 dissimilar stack or to DP1000-GI. The heat generated depends on the complete electrical circuit and evolving contact resistance, not current alone. The reported values should therefore be interpreted as study-specific examples, not universal process recommendations.

8.3 Quality assessment beyond nugget diameter

Nugget diameter is an important geometric indicator, but the source set demonstrates that it is not sufficient by itself. A weld may meet a nominal diameter rule and still fail interfacially. A harder FZ may require a larger critical diameter to ensure pullout. A second pulse may improve cross-tension performance through microstructural and residual-stress changes, or reduce it under a low-current schedule. A joint with a high static load may have a fatigue limitation associated with notch geometry, defects, or material mismatch. A comprehensive acceptance framework should combine geometry, defect inspection, hardness, mechanical testing, and process monitoring.

8.4 Research gaps identified from the supplied papers

The supplied literature suggests several areas where additional work would be useful. First, fatigue data directly comparing IF, HSLA, and AHSS RSW joints under common specimen geometry and test conditions are limited in the supplied set. Second, the combined effects of double-pulse schedules, coating, and fatigue loading require further investigation. Third, predictive models for critical nugget size should incorporate local hardness and toughness rather than relying only on sheet thickness. Fourth, dissimilar stacks with different thicknesses need systematic study of nugget offset, asymmetric HAZ development, and failure location. Fifth, in-process monitoring signals should be correlated with destructive microstructure and fatigue tests to support reliable production control.

8.5 Overall comparison of the four research themes

Table 6. Overall comparison of the four research themes

Theme	Dominant controlling factors	Main lesson from the supplied research
IF steel	Current, time, nugget diameter, coating, loading mode, dissimilarity	Nugget growth raises load capacity, but actual failure mode and HAZ/nugget metallurgy must be verified.
Single/double pulse	Pulse magnitude, duration, interval, remelting, annealing, residual stress	Double pulse can refine or modify microstructure and improve performance, but benefits are condition-dependent.
Fatigue	Nugget diameter, material pairing, defects, joint geometry, cyclic load	Direct RSW fatigue evidence is limited; fatigue qualification must use representative material stacks and loading.
HSLA/AHSS	Alloy chemistry, hardenability, FZ hardness, critical nugget size	Higher strength can increase interfacial-failure tendency; pullout requires adequate nugget size and favourable local properties.

9. CONCLUSION

The literature review demonstrates that resistance spot welding remains a key joining process for automotive sheet structures, but the growing use of IF, HSLA, and AHSS grades requires a more detailed understanding of weld metallurgy and mechanical performance. The main conclusions are:

- RSW quality is governed by the interaction of welding current, weld time, electrode force, electrode geometry, coating, machine characteristics, and current waveform. Weldability lobes and process monitoring are essential for repeatable production.
- IF-steel studies show that increasing current and weld time generally increases nugget diameter and load-bearing capacity over the investigated ranges. However, coating, HAZ grain growth, nugget hardness, and loading mode influence the final response.
- Nugget diameter is important but does not independently guarantee pullout failure. The required critical size depends on sheet thickness, FZ/HAZ properties, steel combination, and loading configuration.
- Dissimilar IF–St52 and HSLA–low-carbon joints show asymmetric nugget formation and different fracture behaviour because of differences in resistivity, thickness, strength, and hardenability.
- Double-pulse RSW changes the thermal history of the weld and can cause partial remelting, recrystallisation, annealing, and altered phase formation. DP600 and DP1000 studies report benefits under specific schedules, while DP1000-GI results show that low-current double-pulse conditions can reduce cross-tension strength and energy absorption.
- HSLA and AHSS welds commonly develop harder fusion zones because of rapid cooling and martensitic/bainitic transformation. The chemistry-dependent hardness profile influences the critical nugget size and failure mode.
- Fatigue performance depends on material combination and nugget geometry. The supplied direct RSW fatigue study confirms differences in fatigue limit among steel combinations. Laser-weld, friction-stir-weld, and drilled-sheet fatigue studies must not be treated as direct RSW evidence.
- Reliable weld qualification should combine process monitoring, weldability-lobe development, metallography, hardness mapping, nugget measurement, static mechanical testing, failure-mode classification, and fatigue testing under representative service conditions.

Overall, the most reliable approach to RSW of advanced high-strength steels is to optimise the complete process–structure–property relationship for each material stack. Future work should integrate in-process monitoring with microstructural characterisation, residual-stress analysis, and fatigue testing so that weld schedules can be selected on the basis of joint reliability and service performance rather than geometric criteria alone.

APPENDIX A: ABBREVIATIONS AND SYMBOLS

Table 7. Abbreviations and symbols

Term	Meaning
AHSS	Advanced high-strength steel

Term	Meaning
BM	Base metal
CTS	Cross-tension strength
DP	Dual-phase steel
FZ	Fusion zone
HAZ	Heat-affected zone
HSLA	High-strength low-alloy steel
IF	Interstitial-free steel
RSW	Resistance spot welding
Rex-zone	Recrystallised zone formed by the second pulse in the cited DP1000 study
S–N curve	Stress or load amplitude versus number of cycles to failure
UTS	Ultimate tensile strength
I	Welding current
R	Electrical resistance
t	Time or sheet thickness, according to context
Q	Heat generated

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