International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

Experimental Design and Validation Framework for Resistance Spot Welding of DP780 and DP980 Steels

Seshabattar Phaneendra[1], Dr. Dheeraj Nimawat[2]

[1]Research Scholar, Department of Mechanical Engineering, JS University, Shikohabad, UP
[2]Supervisor, Department of Mechanical Engineering, JS University, Shikohabad, UP

ABSTRACT

A numerical process optimum becomes an engineering recommendation only after its material identity, measurement basis and physical performance have been established. This paper proposes an experimental and validation framework for resistance spot welding of DP780 and DP980 dual-phase steel sheets. It is a methods protocol derived from an AHSS welding thesis, not a report of completed experiments. The framework separates material qualification, pilot-domain selection, model-building experiments, destructive response measurement and independent confirmation. A three-factor Box–Behnken layout is proposed for current, weld time and electrode force, subject to machine-specific pilot qualification. The preferred common sheet thickness is 1.2 mm, but procurement and coating compatibility must be verified before the design is fixed. Separate specimens are allocated to tensile-shear, cross-tension and metallographic routes so that destructive tests are not misrepresented as repeated measurements on one weld. The protocol defines traceable specimen identifiers, randomization within feasible blocks, centre-point monitoring, data-exclusion rules and model-diagnostic gates. An illustrative workload calculation shows that three specimens for each of two mechanical routes at seventeen design rows across two grades requires 204 welded coupons before pilot, microscopy and confirmation allocations. Numerical results in the source thesis remain explicitly synthetic and are used only to identify candidate questions. The principal output is an auditable chain of evidence through which future measurements could support or reject a model-selected schedule. No actual optimum, material superiority or qualification outcome is claimed.

Keywords: DP780; DP980; resistance spot welding; experimental protocol; measurement traceability; destructive testing; validation; response-surface design.

INTRODUCTION

The purpose of a process-parameter study is not simply to produce a regression equation. It is to establish which statements about a physical system are justified by the observations and how those statements can be reproduced. In spot welding, a list of commanded settings is incomplete unless it is connected to material condition, electrode state, delivered process signals and a defined test response. A defensible experiment must preserve those connections from procurement through final interpretation.

Resistance spot welding creates a localized joint through current flow and electrode force. Its automotive applications and process considerations are treated by Kimchi and Phillips (2023). The present manuscript focuses on experimental governance: how a study of DP780 and DP980 sheets should be designed so that a later optimization claim is supported by traceable evidence rather than by a plausible-looking numerical surface.

The source thesis proposes such an investigation but also includes an explicitly synthetic calculation. Its DP780-labelled and DP980-labelled numerical scenarios are useful for demonstrating statistical modelling and optimization. They are not evidence that sheets were welded or tested. The current protocol responds to that gap by identifying the physical observations still required and the sequence in which they should be collected.

The research question is methodological: what minimum experimental structure is needed to connect a three-factor response-surface study to a credible, bounded process recommendation? The answer involves more than sample count. It requires clear experimental units, material comparability, measurement definitions, planned handling of adverse outcomes and independent confirmation that does not reuse the model-building sample as if it were new evidence.

This paper does not claim a new test standard or a completed validation. It proposes an adaptable framework that must be reviewed against the actual laboratory's equipment, safety procedures and applicable test documents. Numerical planning examples are identified as such. Test-standard dimensions, acceptance thresholds and certification requirements are not invented where the required documents have not been supplied.

The protocol forms part of a three-manuscript set derived from the same thesis. The companion papers address synthetic model diagnostics and preference-sensitive optimization. Unlike those papers, this manuscript's principal output is an executable future research plan. The relationship should be disclosed in any submission, and the proposed methods must not be rewritten in past tense until the corresponding activities have actually occurred.

2. Scope and controlled comparison

2.1 Material systems

The intended joints are DP780/DP780 and DP980/DP980, with a preferred common nominal sheet thickness of 1.2 mm. Similar-grade stacks simplify interpretation by avoiding an additional categorical factor representing dissimilar joining. Common thickness is desirable because it reduces one obvious source of confounding, but the final material system must be defined from actual procurement rather than assumed from the planning document.

A grade label alone is insufficient. The study should retain supplier, product designation, heat or coil identifier, certificate chemistry, coating designation, nominal thickness and measured thickness distribution. If the two grades have different coating systems or come from different suppliers, those differences must be reported. They cannot automatically be separated from grade effects by a regression that contains only current, time and force.

The material comparison should be framed accordingly. With one batch per grade, the experiment can describe the two supplied material systems, but it cannot establish all between-batch variability within each nominal grade. A stronger generalization would require multiple independent batches or an explicitly broader sampling design. The scope of the conclusion should match the scope of procurement.

2.2 Process factors and controlled conditions

The primary factors are welding current, current-application time and electrode force. Other conditions should be selected, documented and held as stable as practical during the main experiment. These include electrode material and face geometry, squeeze and hold settings, cooling conditions, specimen overlap, surface preparation and machine configuration. Holding a condition constant does not mean it is physically unimportant; it means its effect is outside the intended three-factor model.

The thesis planning ranges are 6–10 kA, 150–350 ms and 2.5–4.5 kN. They are not prequalified operating limits. Pilot trials may narrow, shift or reject them. A common physical domain is useful for direct grade comparison only if it is technically appropriate for both supplied materials. Statistical convenience should not force a material into an unsuitable process region.

2.3 Response hierarchy

TS and CT peak loads are proposed as primary quantitative responses because they represent distinct loading configurations. Geometry, failure observations, hardness and process signals provide supporting evidence. The protocol does not assume that every available measurement should become another term in a composite objective. Each response needs a stated purpose, measurement route and interpretation boundary.

For example, a sectional fusion-zone width and a fracture-button dimension are not interchangeable. One is obtained from a prepared section, while the other is associated with a destructive failure geometry. Similarly, peak load and absorbed work are different responses. Work requires an explicitly defined integration interval and displacement measurement, not merely a peak-load record. The study should retain those distinctions throughout analysis and reporting.

International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

Table 1. Proposed scope and evidence status.

Component	Proposed definition	Status
Materials	DP780/DP780 and DP980/DP980	Procurement to verify
Thickness	Common nominal 1.2 mm preferred	Not measured
Factors	Current, weld time, electrode force	Pilot qualification needed
Primary responses	TS and CT peak loads	Separate destructive routes
Supporting evidence	Geometry, hardness, failure, process traces	Methods to finalize
Thesis numeric results	Uncalibrated quadratic scenarios	Synthetic, not experimental

3. Material and equipment qualification

3.1 Incoming-material record

Every sheet should be linked to its procurement record before coupons are cut. The record should identify rolling direction, storage condition and any surface contamination or visible damage. Thickness should be measured at a defined set of locations using a documented instrument. The purpose is not to create an elaborate inspection ritual, but to prevent an unrecorded material change from being interpreted later as a welding-factor effect.

If independent base-material tensile or hardness characterization is performed, its sampling and orientation must be stated. The resulting values should be reported as measurements of the supplied material, not as universal constants for DP780 or DP980. Metallurgical references such as Kou (2020) provide interpretive context, but observed phases and local responses require actual specimen evidence.

Surface preparation should remove uncontrolled contamination through a consistent procedure. It should not silently remove a coating that defines the intended material system. Cleaning materials, drying procedure and handling precautions should be recorded sufficiently well for another laboratory to reproduce the condition. Any deviation should remain linked to the affected coupons rather than being corrected only in a retrospective narrative.

3.2 Machine and electrode record

The welding machine should be identified by type, controller configuration and available monitoring channels. If current is expressed as a root-mean-square value, a mean value or another controller-specific quantity, that convention must be explicit. Milliseconds are preferred for time reporting; if the controller uses cycles, the relevant frequency and interpretation must be recorded. A displayed setting is not automatically equivalent to a measured delivered value.

Electrode specifications should identify the relevant face diameter, tip form, material and dressing procedure. The count of welds since dressing should be recorded. A stabilization sequence may be needed after dressing, but the number and conditions should be established for the actual installation. The protocol does not invent an electrode alloy or tip size where equipment details are missing.
Cooling should be monitored through the variables available and meaningful for the system, such as flow and inlet condition. Interruptions and unusual changes should be logged. If cooling or electrode state drifts systematically during the experiment, the resulting trend can become confounded with run order. Randomization and centre checks help, but they do not replace maintenance and measurement.

3.3 Calibration and synchronization

The force channel should be calibrated or independently checked over the intended working region. Current and voltage monitoring should be verified for the selected waveform and measurement locations. Where dynamic resistance or electrical energy is calculated, current and voltage need an appropriate common time basis. Dividing by a near-zero current can create numerical artefacts, so the calculation interval and any filtering rule should be defined before interpretation.

International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

Electrical energy measured across a specified circuit segment is not automatically the heat absorbed by the nugget. The reporting label should identify the actual measurement boundary. Likewise, an uncalibrated controller estimate should not be presented with the same authority as a traceable measurement. Conejo (2021) provides useful dimensional-analysis background, but dimensional consistency alone does not validate an instrument chain.

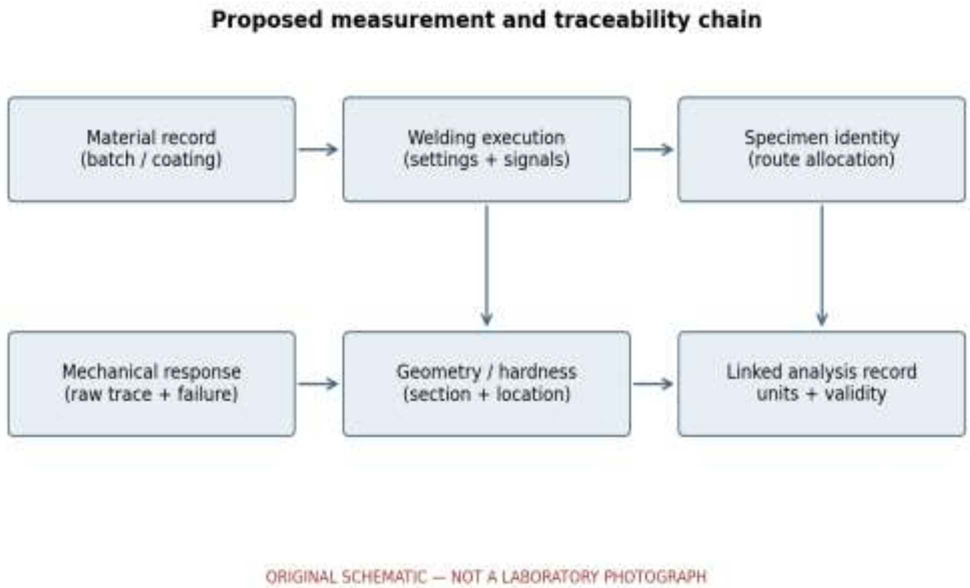

Figure 1. Proposed links between material, process and response records. Original schematic; the measurements remain to be collected.

4. Pilot study and domain selection

4.1 Purpose of pilot trials

Pilot work should establish whether the proposed ranges contain a stable, informative and technically acceptable region. Its purpose is not to collect a few favourable welds and then declare the whole rectangle qualified. The pilot should examine low-response conditions, apparent defect boundaries and repeatability at candidate centres. Any safety limits imposed by the equipment or laboratory take precedence over the planning ranges.

The sequence should be approved by competent laboratory personnel and follow applicable operating procedures. This manuscript does not provide a stand-alone machine operating instruction. Welding hazards and exposure considerations require local assessment; Spiegel-Ciobanu et al. (2020) provide background on hazardous substances in welding and allied processes. Appropriate guarding, ventilation and trained supervision are prerequisites rather than research outcomes.

4.2 Evidence for changing the design

A pilot may show that one grade needs a different current interval or that a common force range is unsuitable. Such findings should lead to a documented design revision before the main campaign. The revision record should state what changed and why. It should also distinguish a change made for technical feasibility from one made after seeing a response pattern that favours a desired conclusion.

If the final domains differ between grades, coded coefficients cannot be compared as if one coded unit represents the same physical change in both cases. Direct grade comparisons should then be made at overlapping physical settings or through a model that explicitly accounts for the different scales. Reporting both coded and physical values prevents an apparently simple coefficient table from masking this issue.

4.3 Pilot data and main-model data

Pilot observations should be retained even if they are not included in the main regression. Their exclusion from that model can be appropriate when the design, measurement procedure or material condition changed, but the reason must be transparent. Selectively discarding unfavourable observations while retaining favourable pilot points would bias the evidence base.

The final analysis plan should state whether any pilot data can enter the main model and under which compatibility conditions. If the pilot primarily determines feasibility, a clean separation may be easiest to interpret. If a sequential design intentionally incorporates pilot points, the complete selection history and resulting design matrix must be reported. Either approach can be defensible when it is planned and traceable.

5. Main experimental design

5.1 Proposed Box–Behnken layout

For three continuous factors and anticipated local curvature, the proposed layout contains twelve edge-midpoint settings and five centre rows. The design has seventeen rows and thirteen unique settings per grade. The same ten-term quadratic basis used in the thesis demonstration is a starting model, not a guarantee of adequate physical fit. A real dataset may show that a smaller domain or a different functional representation is needed.

The layout is not identified as a Taguchi orthogonal array. Although its signed factor columns have useful balance, the full quadratic matrix has a different estimation structure. Beder (2022) provides general linear-model context. In practice, the matrix should be checked for rank after any blocks, missing observations or design revisions are introduced, because the nominal design name does not guarantee that the executed experiment retains its planned properties.

Table 2. Coded and physical design; planning/computational settings, not an executed experiment.

Row	x1	x2	x3	I (kA)	t (ms)	F (kN)
1	-1	-1	0	6.0	150.0	3.5
2	-1	1	0	6.0	350.0	3.5
3	1	-1	0	10.0	150.0	3.5
4	1	1	0	10.0	350.0	3.5
5	-1	0	-1	6.0	250.0	2.5
6	-1	0	1	6.0	250.0	4.5
7	1	0	-1	10.0	250.0	2.5
8	1	0	1	10.0	250.0	4.5
9	0	-1	-1	8.0	150.0	2.5
10	0	-1	1	8.0	150.0	4.5
11	0	1	-1	8.0	350.0	2.5
12	0	1	1	8.0	350.0	4.5
13	0	0	0	8.0	250.0	3.5
14	0	0	0	8.0	250.0	3.5
15	0	0	0	8.0	250.0	3.5
16	0	0	0	8.0	250.0	3.5
17	0	0	0	8.0	250.0	3.5

5.2 Randomization and blocking

Randomization should be implemented within the limits imposed by safe and practical operation. A completely arbitrary sequence may be inappropriate if a machine requires stabilization after major changes, but an entirely ordered sequence can

International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

confound factors with time. The protocol should document the compromise: which changes are randomized, which are restricted and which nuisance variables define blocks.

Potential blocks include production day, electrode-dressing interval and material batch. A block is not simply a convenient label added after testing. Its relationship to factor settings must allow the intended effects to be estimated. If all high-current welds occur after electrode dressing and all low-current welds occur before it, the experiment cannot separate current from electrode condition without further information.

Centre rows should be distributed across the campaign rather than placed consecutively merely for convenience. Their repeated occurrence can help reveal drift when accompanied by actual execution order and process records. A centre response change is a signal to investigate, not proof of a specific cause. Electrode state, cooling, material handling and test-machine behaviour should all remain possible explanations until the records are examined.

5.3 Experimental units and destructive routes
One welded coupon assigned to one destructive test is an experimental unit for that route. A TS test consumes the joint and cannot be followed by an independent CT test on the same intact weld. Separate specimens must therefore be manufactured for the two loading configurations. Metallographic sectioning also requires its own allocation unless a clearly justified post-test examination answers the intended question.

Repeated readings of one hardness indent, repeated image measurements of one section or repeated processing of one force trace are technical repeats. They may help estimate measurement variability, but they do not increase the number of independently produced welds. The dataset should identify both levels so that a statistical analysis does not inflate its sample size through pseudoreplication.

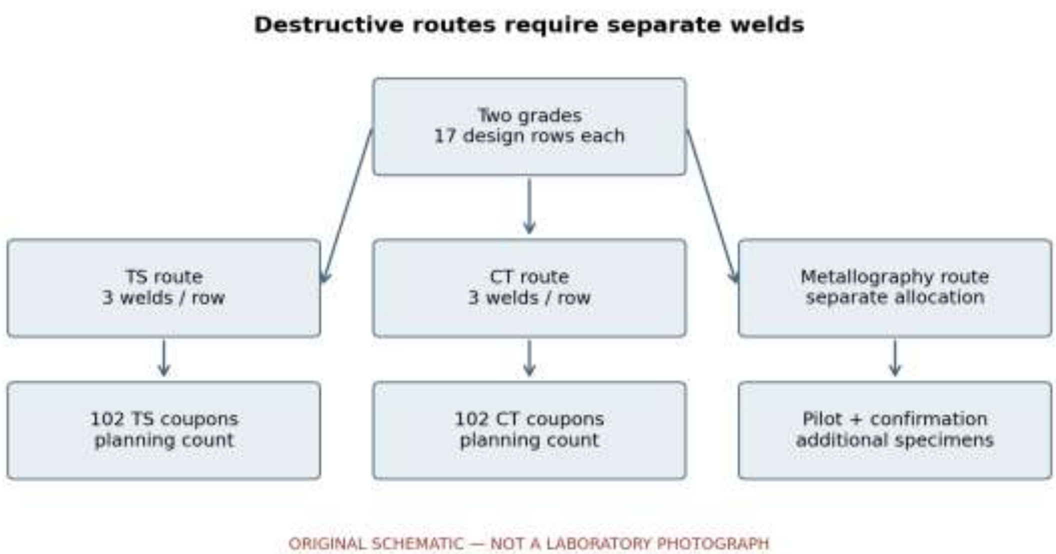

Figure 2. Illustrative separate allocation for destructive response routes. The count is a planning calculation, not completed experiments.

5.4 Illustrative specimen workload
If three independent welds are allocated to each mechanical route at every design row, the main mechanical campaign requires $17 \times 3 \times 2 \times 2 = 204$ welded coupons. The factors in this calculation are design rows, replicates, response routes and grades. This is a planning example, not a completed sample count and not a universal recommendation for adequate power.

Microscopy, pilot work, calibration checks and confirmation require additional allocations. For example, one metallographic coupon at each of thirteen unique settings for each grade would add twenty-six coupons, but that allocation would not by itself estimate section-to-section variability. The final plan should be based on measurement objectives and pilot variance rather than on a desire to keep a round total.

International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

Table 3. Illustrative specimen workload; not a power analysis or completed test count.

Allocation	Calculation	Coupons
Main TS route	17 rows × 3 replicates × 2 grades	102
Main CT route	17 rows × 3 replicates × 2 grades	102
Main mechanical total	102 + 102	204
Optional sectioning example	13 settings × 1 specimen × 2 grades	26 additional
Pilot and calibration	To be determined from actual equipment	Not assigned
Independent confirmation	Precision and decision criteria to determine	Not assigned

6. Measurement plan

6.1 Mechanical testing

The laboratory must select and obtain the applicable TS and CT test documents before manufacturing the final coupons. Specimen geometry, overlap, fixture arrangement, loading rate and reporting conventions should follow the chosen method or be justified as deviations. This protocol deliberately does not invent dimensions or claim compliance with a standard whose full requirements have not been checked.

For each test, retain the raw force–displacement record, specimen identifier, fixture identifier, test date and any operator observation relevant to validity. Peak-load extraction should use a consistent rule. If displacement includes machine or fixture compliance, that limitation must be acknowledged before interpreting an integrated work value as specimen energy absorption. A secondary response should not be added merely because the software can calculate it.

Failure classification should be supported by photographs and a predefined descriptive scheme. Ambiguous cases should remain identifiable rather than being forced into a favourable category. The scheme should distinguish observation from interpretation: a visible fracture path can be described, while a metallurgical explanation may require sectioning or other evidence. The numerical load and the failure description should remain linked to the same specimen record.

6.2 Metallography and geometry

The sectioning plane, mounting procedure, grinding and polishing sequence, etching method and image scale should be documented. A section that misses the nugget centre may underestimate a maximum width, so the measurement definition should state what is being estimated and how the plane is located. Multiple images of one section do not automatically provide independent geometric replicates.

A measured fusion-zone width should not be relabelled as button diameter. Surface indentation likewise needs a defined datum and measurement method. If two perpendicular dimensions are averaged, the individual values should be retained. Reporting a single mean without its measurement convention can obscure both anisotropy and operator judgement.

Actual images should include scale information and specimen identity in the underlying record. Image processing should be limited to disclosed operations that preserve the evidence, such as consistent brightness adjustment or cropping for presentation. Features must not be inserted, removed or generated to match a preferred microstructural explanation. The illustrations in this manuscript are schematics of the proposed workflow, not substitutes for those future images.

6.3 Hardness and local material response

A hardness traverse should specify load, dwell convention, indent spacing, traverse location and treatment of invalid impressions according to the selected method. The purpose is to compare defined local regions, not to produce an attractive profile without spatial traceability. If several traverses are made on one section, their nesting within that specimen should be retained in analysis.

International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

Local hardness does not directly establish a phase fraction, residual stress or fracture toughness. It can support an interpretation when combined with suitable microstructural and mechanical evidence. A claim of heat-affected-zone softening requires measured local values and a defensible reference region. It cannot be inferred from the synthetic load equations in the thesis.

6.4 Process signals

Where instrumentation permits, record delivered current, voltage, electrode force and relevant timing signals. Sampling rate, synchronization, sensor locations and filtering should be documented. The study should distinguish missing channels from channels that were measured but excluded. A missing voltage trace, for example, means that a reliable electrical-energy calculation may not be available; it does not justify substituting an invented constant resistance.

Signal features should be chosen for a stated purpose. A maximum, integral or time-to-peak can summarize a trace, but each discards information and may depend on processing choices. The raw trace should remain available so that a later reviewer can assess whether the feature captures a real process event or an artefact. Feature extraction should ideally be frozen before comparing preferred and nonpreferred schedules.

7. Data management and analysis

7.1 Traceability structure

A specimen identifier should link grade, batch, design row, replicate, response route and execution block. The identifier should not encode a favourable or unfavourable outcome. Separate fields should record commanded settings and measured delivered quantities. This allows the analyst to distinguish an intended treatment from the process actually delivered without overwriting the original plan.

The data structure should retain units, missing-value reasons and validity flags. A blank cell, a zero response and a failed specimen are not interchangeable. If a test is invalid because of fixture malfunction, that is different from a valid low-load failure. Preserving these distinctions prevents an apparently clean analysis table from hiding the most important experimental events.

Table 4. Minimum proposed record structure.

Record group	Fields to retain	Purpose
Material	Grade, batch, certificate, thickness, coating	Define tested system
Design	Assigned factors, row, block, replicate	Preserve intended treatment
Execution	Actual order, electrode state, delivered signals	Identify delivery and drift
Mechanical	Route, fixture, raw trace, failure images	Trace response definition
Metallography	Section plane, scale, preparation, measurements	Support local geometry claims
Validity	Missingness, exclusions, repeat links, reasons	Prevent silent selection
Analysis	Code version, units, model, diagnostics	Enable reproduction

7.2 Exclusions and repeats

Rules for excluding a test from a primary analysis should be defined before outcomes are reviewed. Examples of potentially invalid tests include documented instrument malfunction or a specimen that demonstrably does not match the assigned geometry. A low load, unusual failure mode or inconvenient residual is not automatically an exclusion reason. Every excluded record should remain in the archive with its reason and any replacement specimen identifier.

Repeating a test does not erase the original observation. If a repeat is commissioned because an outcome is surprising, the analysis should acknowledge the adaptive decision. Otherwise, the reported dataset may favour expected results simply because unexpected ones were given more opportunities to be replaced. A transparent protocol makes such decisions visible rather than pretending that the final dataset arose in one uninterrupted planned sequence.

7.3 Model fitting and diagnostics

The initial model contains linear, squared and pairwise interaction terms for the three factors. Each response is analysed separately before any composite objective is introduced. The analysis should report coefficient estimates, uncertainty, residual behaviour and the model's supported domain. A large R^2 is not a sufficient acceptance gate, particularly when a small design is used to estimate many coefficients.

Replication should be analysed at the correct level. If independent welds are modelled individually, their within-setting variation contributes to error estimation. If row means are used, the variance and degrees of freedom refer to those means. The investigator should not mix the two conventions. Unequal replication, heteroscedasticity or session effects may require a model that reflects those features rather than an unmodified textbook ANOVA table.

Residual plots should use real execution order when assessing drift. A pattern may suggest a problem, but interpretation requires process records. Lack-of-fit assessment should be response-specific and should retain adverse results. The source thesis's synthetic CT lack-of-fit example shows why favourable overall fit and an unfavourable diagnostic can coexist; it does not predict what the physical experiment will show.

7.4 Validation design

Validation partitions should respect the experimental hierarchy. Placing replicates from the same setting or block in both training and validation can make prediction appear easier than it will be for a genuinely new setting or session. The intended deployment question should determine the partition. Predicting another weld at a known setting, another setting within the domain and another material batch are different tasks.

Model rank must be checked after withholding data. In the proposed three-factor layout, removing all centre rows makes the intercept inseparable from the common component of squared terms. A full quadratic centre-fold prediction is then not uniquely identifiable. This structural issue should be recorded rather than hidden by a software routine that returns one generalized-inverse solution.

8. Independent confirmation and decision gates

8.1 Candidate selection

After a satisfactory model is obtained, optimization can identify candidates under agreed response priorities and constraints. The decision criteria should be set before inspecting which candidate looks most favourable. The physical study should not automatically adopt the synthetic thesis settings. Those values can inform a question to investigate only after pilot qualification demonstrates that the relevant region is appropriate for the actual equipment and material.

A small candidate set is preferable to a single unexplained coordinate triple. It can include the nominal model-selected point, a nearby interior alternative and a reference schedule established during pilot work. Preference-sensitive alternatives may also be useful if TS and CT priorities are uncertain. Each candidate should have a clear reason for inclusion and a predefined comparison criterion.

8.2 Fresh specimens and independent sessions

Confirmation requires newly produced specimens that were not used to fit or tune the model. Wherever the intended claim concerns repeatability across sessions, confirmation should include a separate session with the relevant setup and material traceability retained. New random numbers from the same surrogate do not meet this requirement. They test the numerical generator, not the welding system.

The confirmation sample size should be selected using the desired precision, acceptable error rate and variance information from pilot or main experiments. The illustrative three-replicate planning example is not a power analysis. A decision about equivalence or minimum acceptable performance may require a different sample size from a decision about detecting a mean difference. The statistical question must be defined before the count is chosen.

International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

8.3 Acceptance criteria and uncertainty

Acceptance should use predefined physical criteria, including any mandatory geometry or failure restrictions, rather than rely solely on mean predicted load. Confidence or prediction intervals should be interpreted according to what they describe. An interval for a mean is narrower than the distribution of individual weld outcomes and cannot be used as though it guarantees every future joint will meet a threshold.

If confirmation disagrees with prediction, the response is not automatically to adjust the model until the selected point appears successful. The investigation should examine material identity, delivered process values, measurement validity and the adequacy of the original domain. A revised model may be justified, but the revised candidate then needs its own independent assessment. The distinction between model development and confirmation should remain intact.

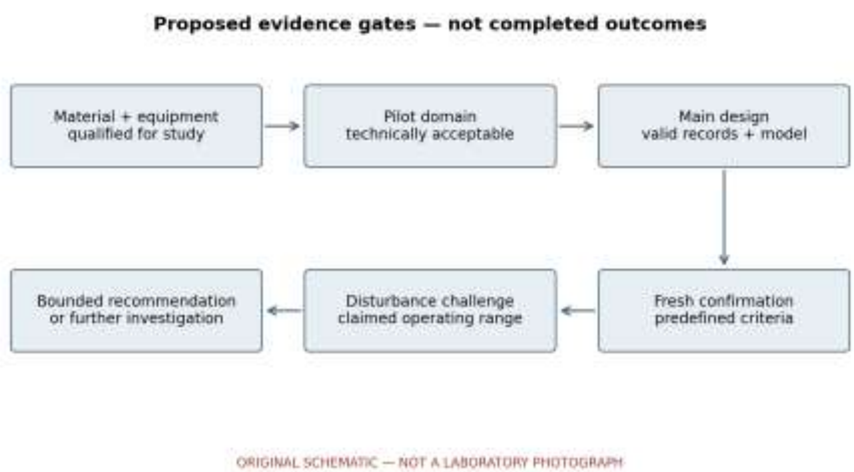

Figure 3. Proposed validation gates. Passing any gate must be demonstrated from physical records; no gate is represented as already passed.

8.4 Robustness challenge

Once a candidate meets the initial confirmation criteria, deliberate local changes can assess sensitivity to relevant process variation. The disturbance sizes should come from machine capability or a justified operating tolerance, not simply from the synthetic example. Both one-factor and combined disturbances may be informative, especially where interactions are important. The resulting claims should be limited to the disturbances actually tested.

Electrode-life and material-batch robustness require additional designs. They cannot be inferred from a few nearby current or time settings. A process that is stable over one fresh-electrode session may behave differently after prolonged use. If the intended claim is production readiness, the validation programme must include the dominant production disturbances rather than assume them away.

9. Expected methodological outputs

The primary outputs of this protocol are a traceable material-and-process dataset, response definitions that match the measurement routes, a statistically auditable model and an independently assessed candidate set. These are expected deliverables, not completed findings. The protocol does not predict which grade will perform better or which factor will dominate. Those questions remain open until measurements are available.

The specimen-workload arithmetic is one concrete planning result. A three-replicate mechanical allocation across two routes and two grades yields 204 coupons for the seventeen-row main design. That count makes clear why an apparently small design can require substantial laboratory effort. It also shows why microscopy and confirmation should be budgeted separately rather than assumed to be obtainable from the same destructively tested welds.

Another methodological result is the identification of design dependencies. Centre rows support both curvature estimation and repeatability assessment at the chosen analysis scale. Execution blocks can protect against nuisance variation only when they are not confounded with the factors. Measurement repeats do not substitute for independently manufactured specimens. These are structural findings about the proposed programme, not empirical conclusions about AHSS metallurgy.

International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

The planned visual evidence has a similarly explicit role. Photographs should document actual specimen condition and failure appearance. Micrographs should support claims about local structure only when preparation and scale are traceable. Process traces should show delivered signals with their measurement boundaries. Schematic pictures in a methods paper explain these routes but cannot replace the observations they are designed to organize.

DISCUSSION AND LIMITATIONS

10.1 Feasibility and resource constraints

The protocol is intentionally modular. A laboratory without reliable synchronized voltage measurement can still perform a defensible mechanical and metallographic study, provided it does not claim measured electrical energy. A laboratory without capacity for multiple material batches can still describe its supplied material systems, provided it does not generalize to all products within each grade. A smaller claim supported by good evidence is preferable to a broader claim supported by assumed measurements.

Resource constraints should be addressed through design choices rather than hidden compromises. Reducing replication affects precision; reducing the number of unique settings affects model support; eliminating a response route changes the decision problem. These are different sacrifices. The investigator should identify which scientific question remains answerable after each change instead of preserving the original abstract unchanged.

10.2 Avoiding retrospective certainty

A protocol should not promise that an optimum will exist inside the initial domain or that every planned response will show a smooth trend. A real study may reveal an unsuitable range, a discontinuity, a strong nuisance effect or insufficient repeatability. Such findings are scientifically informative when reported honestly. The purpose of planning is to make those outcomes interpretable, not to guarantee a favourable conclusion.

The numerical thesis example must therefore remain separate from the expected physical results. Its selected settings can be used to illustrate how a candidate is represented, but not to define the answer that the experiment is supposed to confirm. Otherwise, pilot choices, exclusion decisions and model selection may become biased toward reproducing a value that was originally assumed.

10.3 Publication and data integrity

The eventual experimental paper should state what was actually done, including deviations from this protocol. Authorship, institutional affiliation, funding and conflicts of interest must reflect real contributions and circumstances. AI-assisted drafting does not remove the authors' responsibility to verify every technical claim, citation and image. Similarity checking is a useful editorial step, but a low similarity score is not evidence of experimental validity or originality of the underlying research question.

Related manuscripts should disclose shared data and avoid presenting the same result repeatedly as independent evidence. The modelling and optimization demonstrations are already connected to this proposed protocol. If future physical data are collected, the publication strategy should distinguish new empirical evidence from earlier synthetic illustrations. Reusing background text should also be handled transparently according to the target publication's requirements.

11. Worked planning and audit examples

11.1 Precision planning is response-specific

The illustrative three-specimen allocation is a workload example rather than a universal sample-size rule. To see the distinction, consider the approximate large-sample expression $n = (1.96s/h)^2$ for estimating a mean with a desired two-sided ninety-five-percent half-width h when independent normal variation with standard deviation s is assumed. The expression is only a planning approximation; a small-sample calculation should account for uncertainty in s and the appropriate quantile.
If one provisionally uses $s = 0.18$ kN and $h = 0.10$ kN, the arithmetic gives about 12.45, which rounds upward to thirteen specimens. If $s = 0.10$ kN and $h = 0.05$ kN, it gives about 15.37, which rounds upward to sixteen. These standard deviations are borrowed solely as numerical examples from the synthetic thesis assumptions. They are not pilot estimates and must not be used to claim that thirteen or sixteen physical welds are sufficient for this study.

The example shows why the response, precision target and variance source must be stated together. A power calculation for detecting a difference between two schedules would ask a different question and would also require a meaningful effect size. A reliability claim about individual welds exceeding a limit would require another formulation. The final experiment

International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

should choose the statistical question first and then determine the allocation using actual or defensibly external variance information.

11.2 Audit case: a delivered-current discrepancy
Suppose a coupon is assigned to a nominal current but the recorded trace shows that the delivered waveform does not meet the predefined process-validity rule. The original assigned setting and measured trace should both remain in the record. The specimen may be excluded from a per-protocol factor analysis under a documented rule, but its existence should not disappear. The exclusion reason, decision date and any replacement coupon should be linked.

This case differs from a valid weld that carries a low load. The first raises a treatment-delivery question; the second may be genuine evidence about the response at an implemented setting. Treating both as bad specimens would blur process compliance with scientific outcome. The protocol should define those categories before the operator knows which result is inconvenient.

11.3 Audit case: disagreement between geometry and load
Suppose a schedule produces a comparatively large measured sectional width but an unfavourable CT response. The correct response is not to discard one measurement because it conflicts with an expected size–strength story. The measurements may describe different aspects of the joint, and the fracture path, local material condition or section location may be relevant. The paired records provide a basis for investigation rather than a reason to force agreement.

A follow-up examination should identify exactly which specimens are compared. A micrograph from one weld cannot automatically explain the failure of another unless the sampling relationship and repeatability are established. If the images are representative examples selected from a larger set, the selection rule should be stated. This avoids presenting one visually persuasive image as though it were a complete quantitative account of the process condition.

11.4 Audit case: session drift at the centre
Suppose centre-point loads decline over the execution sequence while the commanded settings remain constant. That pattern could indicate process drift, but it does not identify its cause. The investigation should compare electrode records, cooling conditions, material handling, delivered signals and test-session information. A current coefficient should not absorb the trend simply because higher-current settings happened to occur later.

If the drift is substantial, the analysis may require a block term, a revised experimental sequence or additional observations. The decision should be recorded before claiming a stable response surface. A post hoc correction can be scientifically useful, but it should not be described as though it were part of the original design. The distinction helps readers assess how much of the result is confirmatory and how much is an exploratory repair.

11.5 Audit case: confirmation failure
Suppose fresh confirmation welds at a model-selected schedule do not meet the predeclared comparison criterion. The result should be reported as a failed or inconclusive confirmation under that criterion, not redefined as success because one specimen achieved a high peak load. The next step is diagnosis: verify material and process identity, examine prediction uncertainty and inspect whether the candidate lies near a poorly supported or unstable region.

If a revised model is fitted using those confirmation observations, they become part of model development. Another independent assessment is then needed for the revised selection. This sequence may be perfectly reasonable scientifically, but it should remain visible. Otherwise, a repeatedly adjusted model can appear to have passed an independent test when every test has actually been used to tune it.

11.6 Minimum release package for a physical claim
Before releasing a process recommendation, the study should assemble the material certificates, executed design, specimen allocation, calibration evidence, raw mechanical traces, geometry records, failure images, analysis code and confirmation report. The package need not expose confidential commercial information publicly, but the scientific chain should be auditable by authorized reviewers. Any redaction should preserve the information necessary to interpret the claimed material and process domain.

The final claim should identify what remains outside that package. A study with one sheet batch and fresh electrodes should not imply demonstrated robustness across suppliers and electrode life. A study of similar-grade joints should not imply validated dissimilar stacks. Stating these boundaries is not a weakness in the conclusion; it defines the conditions under which the evidence has meaning and makes a subsequent extension scientifically testable.

11.7 Preparing an executable laboratory handover

The final handover should translate the protocol into a run sheet that can be followed without interpreting the manuscript during operation. Each planned specimen should have an identifier, assigned material, intended settings, response route and block. Fields for actual execution time, delivered signals and deviations should be available before welding begins. This reduces the risk that important information is reconstructed from memory after the outcome is known.

The run sheet should also distinguish authorization from observation. An operator's confirmation that a setup is ready is not a measured response, and a supervisor's approval of a deviation is not evidence that the deviation has no scientific effect. Keeping these fields separate allows later analysis to identify which parts of the programme followed the original plan and which require a sensitivity analysis or a narrower conclusion.

Training should cover measurement definitions as well as machine operation. Two operators can produce inconsistent geometry data if one reports the largest visible sectional width while another reports an average across selected directions. A short shared measurement exercise on nonstudy material can identify such differences before the main campaign. The purpose is consistency of interpretation, not removal of all operator variability through undocumented judgement.

Davim (2021) provides broader welding-technology context, including quality-related topics, while Chen et al. (2024) address robotic welding systems. These sources reinforce the need to treat the equipment and measurement arrangement as part of the study definition. They do not prescribe the missing laboratory details in this protocol. Those details must be completed from the actual installation and the selected test documents.

The handover should end with a clear stop-and-review rule. Unexpected safety issues, loss of calibration validity or a material-identity discrepancy should trigger the laboratory's established review process rather than an improvised attempt to complete the planned count. A scientifically useful dataset is not defined by whether every cell in the original spreadsheet is filled. It is defined by whether the observations can be trusted, interpreted and connected to the claim that the study ultimately makes.

CONCLUSIONS

An AHSS spot-welding recommendation requires a continuous chain from material identity and delivered process conditions to defined responses, model diagnostics and independent confirmation. The proposed framework supplies that chain while keeping the source thesis's synthetic results separate from measurements that have not yet been made.

The seventeen-row Box–Behnken layout is a proposed model-building design, not a prequalified process recipe. Separate destructive-test routes, correct replication levels, randomized or appropriately blocked execution and traceable exclusions are necessary for interpretable results. The illustrative main mechanical allocation requires 204 welded coupons before pilot, metallography and confirmation work are included.

No physical optimum or grade superiority is established by this protocol. The next scientific step is pilot-qualified execution with actual materials and calibrated equipment. A later recommendation should be limited to the tested material system, measurement definitions and disturbance conditions, with unresolved uncertainty reported rather than replaced by numerical confidence.

Declarations and relationship to the thesis

This manuscript is a proposed methods protocol derived from the supplied thesis. No experimental work is represented as completed. The companion papers analyse an explicitly synthetic dataset; they do not supply physical validation for this protocol. Thesis author, institution, year and repository details must be added before submission. Actual authors must complete affiliations, funding, contributions and conflict-of-interest declarations. AI assistance was used in drafting and figure preparation and should be disclosed under the target journal's policy. The figures are original explanatory schematics, not photographs of specimens or equipment. All numerical specimen counts are planning calculations, not an inventory of completed tests.

International Journal of Engineering Fields (IJEF)
Volume 3, Issue 3, July-September, 2025
Available online at: https://journalofengineering.org

REFERENCES

1. Beder, J. H. (2022). Linear models and design. Springer. https://doi.org/10.1007/978-3-031-08176-7
2. Chen, M., Ren, W., & Jiang, Y. (2024). Technologies of robotic welding. Springer. https://doi.org/10.1007/978-981-97-3149-7
3. Conejo, A. N. (2021). Fundamentals of dimensional analysis: Theory and applications in metallurgy. Springer. https://doi.org/10.1007/978-981-16-1602-0
4. Davim, J. P. (Ed.). (2021). Welding technology. Springer. https://doi.org/10.1007/978-3-030-63986-0
5. Kimchi, M., & Phillips, D. H. (2023). Resistance spot welding: Fundamentals and applications for the automotive industry (2nd ed.). Springer. https://doi.org/10.1007/978-3-031-25783-4
6. Kou, S. (2020). Welding metallurgy (3rd ed.). Wiley. ISBN 9781119524816. https://www.wiley.com/en-us/Welding%2BMetallurgy%2C%2B3rd%2BEdition-p-9781119524816
7. Spiegel-Ciobanu, V. E., Costa, L., & Zschiesche, W. (2020). Hazardous substances in welding and allied processes. Springer. https://doi.org/10.1007/978-3-030-36926-2
8. Source thesis (unpublished document supplied for this work): Optimization of Process Parameters for Spot Welding of Advanced High-Strength Steels. Author, institution and year were not supplied and must be completed before submission. The source thesis is separate from the published-book references above.