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# In-Process Quality Prediction in Rail Flash Butt Welding: Testing the Sufficiency of Scalar Process Signatures

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**Abstract:**
Continuously welded rail (CWR) has displaced the fishplated joint as the standard permanent way construction throughout the world because the mechanical discontinuity at a bolted joint is the origin of track deterioration, rolling noise, vehicle dynamic loading, and rail-end fatigue. This study establishes a data-driven diagnostic framework to evaluate the sufficiency of current scalar process acceptance parameters against a documented single-case joint failure that passed traditional non-destructive inspections but suffered a flat brittle fracture during press straightening. By constructing a systematic process signature database of 79 weld cycles across R260 and R350HT rail grades on two nominally identical Schlatter installations, this work evaluates thirteen scalar descriptors—including newly derived velocity, energy, and volumetric index features. Statistical evaluations via Welch's unequal-variance t-test reveal that despite identical processing standards, the two machines exhibit significant divergent baselines ($p < 0.01$) across 11 key operational parameters, proving that raw numerical acceptance thresholds are non-transferable. Most critically, an out-of-sample sufficiency evaluation demonstrates that all thirteen summary scalar parameters of the failed joint resided safely within their corresponding $\pm 3\sigma$ control limits, meaning traditional scalar-value statistical process control is fundamentally blind to intra-cycle variations. Continuous trace analysis using a Schlatter WeldAnalyzer confirms the fracture originated from a two-second platen velocity discontinuity during final flashing, driving flashing arc extinction and a localized 8% secondary current spike that left hidden unexpelled oxides at the bond line. To address this blind spot, a three-layer transferable solution framework is proposed: upstream calibration gating rules, intra-cycle trace monitoring rules operating on temporal velocity/current envelopes, and machine-stratified scalar control charts.

***Keywords*— *Flash Butt Welding, Process Signature Analysis, Statistical Process Control, Root-Cause Diagnostics, Structural Integrity, Heat Affected Zone, Rail Manufacturing.***

## I. INTRODUCTION

### *A. Background and Technical Context*

The permanent way infrastructure of contemporary global rail networks relies heavily on continuous welded rail (CWR) architectures to eliminate the mechanical discontinuities inherent in traditional fishplated bolted joints. Bolted configurations impose cyclic shock profiles that accelerate localized ballast settlement, track alignment degradation, wheel-rail contact fatigue, and structural rail-end failure. By transitioning to a continuous structure, the dynamic service stresses are transferred directly down the length of the rail elements, imposing severe combinations of cyclic bending, high wheel contact loading, and high thermal variations over operational lifespan targets spanning decades.

Consequently, the processing lines attached to advanced rolling mills must deliver heavy weld joints with mechanical and metallurgical properties that closely match those of the pearlitic parent rail matrix. Flash butt welding stands as the premier automated method for creating high-integrity joints in heavy-haul and high-speed tracks, executed via both stationary mill units and mobile track machines. The process uses electrical resistance heating, combined with continuous mechanical platen displacement, to produce an autogenous, high-strength bond line without the addition of filler metal.

### *B. The Flash Butt Welding Cycle*

The operational sequence of an automatic flash butt welding cycle is divided into four distinct phases. These stages are monitored by control systems that track platen travel (s), secondary welding current (I), and axial forging force (F):

1) Preheat: The rail ends are brought into intermittent contact and separated under a managed voltage profile. This cycles current in controlled pulses to raise the bulk cross-sectional temperature and establish a tight axial thermal gradient. The records reviewed in this work reveal stable preheat periods with an on-time of 3.6 to 4.1 s and an off-time of 1.27 to 1.55 s.

2) Burnoff: The platen advances at a low initial velocity to burn off irregularities from sawn or machined rail ends, creating a clean, uniformly active surface.

3) Final Flashing: The platen accelerates smoothly according to a programmed profile while microscopic contact points (bridges) continuously form, melt, and explode. This action expels surface oxides and heats the material to form a ductile, localized zone. The platen speed must increase progressively to maintain continuous

  

bridge formation as interfacial electrical resistance falls; otherwise, solid contact will develop.

4) Upsetting (Forging): The machine closes its platens at high speed under high axial force, extruding molten or oxidized metal away from the weld plane and consolidating the joint in a solid state. Post-weld operations include automated trimming of the hot extruded flash.

### *C. Quality Requirements and Governing Standards*

Product compliance and acceptance are governed by the strict engineering criteria of the Research Designs and Standards Organisation (RDSO) under Indian Railway Standard specification IRS T-12, the European standard series EN 14587-2 for fixed plant manufacturing, and the American Welding Society guidelines (AWS C1.1). Compliance requires strict geometric alignment control, ultrasonic testing (UT), and periodic transverse slow bend destructive sampling. Under current codes, standard process acceptance relies on extracting summary scalar metrics from the weld cycle log. Metallurgical compliance—such as keeping the heat affected zone (HAZ) width within a strict 40 mm threshold along the entire profile and maintaining a pearlite microstructure free of brittle martensite or bainite (finer than ASTM grain size 4.0 at 100× magnification)—is verified via destructive sampling of a single joint per test lot.

### *D. Motivation and Industrial Significance*

Contemporary quality assurance remains fundamentally retrospective; non-destructive evaluations intercept flaws only after the joint is fully processed, while destructive testing sacrifices the joint entirely. This creates an operational blind spot where systematic machinery drift or component degradation can generate consecutive defective welds before confirmation is caught downstream. Furthermore, the downstream penalty of a rejected weld severely constrains plant efficiency. In an integrated heavy rail mill, the finishing blocks are tightly coupled to the upstream output of the rolling mill. Any rework loop—requiring a 260-metre panel to be cut back, re-machined, and re-welded—stalls line flow and creates cooling bed congestion. A 30-day delay analysis conducted over September 2025 at the studied mill reveals that the finishing area processed approximately 17 rails per hour against a rolling rate of approximately 20 rails per hour, a deficit of about three rails per hour. The consequence was cooling bed congestion: 129 recorded bed-full events over the month, totalling 66 hours 43 minutes of lost rolling time, an average of 133.4 minutes per day, and a mill availability loss of 9.27 per cent against a total study duration of 720 hours. The downtime was distributed almost evenly across the three shifts, at 33.5, 31.3 and 35.2 per cent respectively, which establishes it as a systemic process constraint rather than an operator-dependent or shift-specific effect.

## II. REVIEW OF LITERATURE

### *A. Fundamentals of the Flashing Arc and Bridge Dynamics*

The physical description of flash butt welding rests on the behaviour of the molten bridge. Contact between microscopic asperities on the two faying surfaces establishes current paths of very small cross-section; the resulting current density is sufficient to melt and then vaporise the bridge, which is expelled explosively. The cycle of formation, heating and destruction repeats at a rate governed by the platen advance velocity and by the instantaneous interfacial resistance, and each event removes a small quantity of material while depositing heat into the rail ends. Two consequences follow that are essential to the present work. First, the axial temperature distribution is established by the cumulative statistics of many thousands of individual bridge events rather than by any single continuous heating process, which means that the uniformity of the flashing action, and not merely its total duration, governs the uniformity of the thermal field. Second, the interfacial layer at the instant of upset consists of molten metal and its oxidation products, and the quality of the joint depends on the completeness with which this layer is extruded. Both consequences imply that a disturbance which alters the rate or regularity of bridging, without altering the total flashing time or distance, will alter the joint without altering the scalar record.

### *B. Metallurgy and Transformation Behavior of Pearlitic Rail Steels*

Carbon rail steels of the R260 class are fully pearlitic in the as-rolled condition. Strength and wear resistance depend principally on the pearlite interlamellar spacing, which is itself set by the transformation temperature and hence by the cooling rate through the eutectoid region. Prior austenite grain size governs toughness and the propagation resistance of the transformation product. Head-hardened grades such as R350HT are produced by accelerated cooling of the rail head, giving a finer pearlitic structure in the head while leaving the web and foot substantially in the as-rolled condition. This asymmetry is directly relevant to the interpretation of heat affected zone measurements, because the response of the head to a welding thermal cycle differs between the two grades while the response of the web and foot does not. Where the cooling rate through the transformation range is high enough—because of a narrow thermal field, an unusually cold ambient, an accelerated post-weld cooling practice or local alloy segregation—martensite or bainite may form at or near the bond line. Both are unacceptable in a rail weld: they are hard, low in toughness and act as crack initiation sites under the bending and contact stresses of service. Their absence is therefore a mandatory acceptance criterion, verified by micro-examination on sampled joints.

  

### C. Defect Taxonomy and Signature Relationships

The defect taxonomy of rail flash butt welds is well established and the formation mechanism of each class is understood at least qualitatively. Table I provides a structural comparison of observed defect classes, mapping each mode to its physical mechanism and evaluating how it impacts the machine's scalar totals versus its intra-cycle signature.

| S No. | Defect Mode | Attributed Processing Mechanism | Expected Signature Impact |
|---|---|---|---|
| 1 | Sticking During Flashing Phase | Inadequate platen velocity profile causing solid contact. | Intra-cycle only: current spike and travel plateau. |
| 2 | Blowhole / Porosity | Gas entrapment from surface moisture or flashing interruptions. | Secondary intra-cycle signature shift following sticking. |
| 3 | Flat Spot / Lack of Solid-State Bond | Insufficient heating or low forging upset force. | Scalar total: lower upset travel distance or low heat input index. |
| 4 | Oxide Inclusion (Grey Spots) | Incomplete expulsion of molten layer during forging phase. | Partly scalar (upset ratio), partly intra-cycle trace shape. |
| 5 | Heat Affected Zone Over-Softening | Excessive energy input or prolonged thermal cycles. | Scalar total: high heat input index and total heating time. |
| 6 | Geometric Cross-Section Misalignment | Loss of clamping force, jaw wear, or transducer drift. | Not recorded in signature; detected dimensionally. |

TABLE I: Defect Taxonomy, Mechanisms, and Signature Relationships

## III. PROBLEM IDENTIFICATION AND CAUSAL MODELING

### A. Statement of the Problem

Rail flash butt welding operations experience a persistent, low-level rate of joint rejection that is detected only after the weld has been made. The rejections are not randomly distributed: they cluster in time and by machine, which indicates systematic process causes rather than stochastic variation. Because detection occurs downstream of production, the causal link back to the specific process condition that produced the defect is broken, and corrective action is consequently applied on the basis of experience and inference rather than of evidence. A sharper form of the problem emerged from the failure investigation: a joint that fractured in a brittle manner under press straightening had been produced with process parameters that were, on the plant record, entirely unremarkable. The defect that caused the fracture was visible in the recorded trace of the weld cycle. It was not visible in any of the scalar values by which that cycle had been judged. The problem, stated precisely, is therefore not merely that detection is retrospective; it is that the retained scalar record may be incapable of supporting prediction at all.

### B. The Documented Joint Failure Case

On 7 February 2026 during the night shift, a production joint identified as 06650226BSP2, in R260 grade 60E1 section, was welded on machine 31102 at 20:39:38 hours. During the subsequent press straightening operation the joint fractured completely. The fracture was reported immediately and a formal investigation was conducted in the presence of the third-party inspection agency representative. The scalar parameters recorded by the plant monitoring system for the failed joint are given in Table II.

  

| Parameter | Tool Log Value | Factory Operating Assessment |
|---|---|---|
| Secondary RMS current | 61.3 kA | Within range |
| Burnoff time | 29.3 s | Within range |
| Burnoff distance | 5.8 mm | Within range |
| Preheat on time | 3.98 s | Within range |
| Preheat off time | 1.41 s | Within range |
| Flashing time | 13.3 s | Flagged for review |
| Flashing distance | 11.5 mm | Flagged as low, indicating sticking |
| Butting force | 463.2 kN | Within range |
| Butting distance | 15.5 mm | Within range |

**TABLE II: Recorded Summary Parameters of Failed Joint 06650226BSP2**

The travel trace explains both. The platen advance during final flashing exhibits two distinct velocity regimes rather than the single progressive acceleration the programme calls for. An initial phase of slow, constant, linear advance is followed by a later phase of progressive acceleration. During the linear phase the advance velocity was insufficient to sustain continuous bridge formation and destruction. The rail ends made solid contact and held it for more than two seconds — visible as a plateau in the travel curve and as the current excursion described above. Resistive heating continued throughout this period while material expulsion ceased. When flashing resumed under the progressive velocity regime, the interfacial condition had already been established: overheated material, an unexpelled oxide layer, and entrapped gas. Visual examination of the fractured joint recorded a relatively flat, brittle-type failure pattern rather than a ductile tearing mode, indicating a metallurgically weak bond at the weld interface.

### *C. Upstream Failure Root Isolation*

Review of the last calibration performed before this weld, conducted on 6 January 2026, revealed that the condition had been announced in advance. The relevant record is given in Table III.

| Monitored Parameter | Logged Value | Target Range Boundaries | Evaluation Status |
|---|---|---|---|
| Offset Pv | 0.00 V | -0.25 to 0.25 V | Pass |
| Offset Pr | 0.00 V | -0.25 to 0.25 V | Pass |
| Offset Travel | 0.04 V | 0.00 to 0.50 V | Pass |
| Scaling Travel | 7.69 mm/V | 6.95 to 7.69 mm/V | FAIL |
| Force v | 890.4 kN | 792.0 to 968.0 kN | Pass |
| Force r | 710.7 kN | 631.8 to 772.2 kN | Pass |
| Current 700 | 113.78 kA | 113.65 to 130.75 kA | Pass |

**TABLE III: Upstream Machinery Calibration Log Analysis**

  

## IV. METHODOLOGY

### *A. Research Configuration and Data Structure*

The study follows a correlational design built on retrospective plant records, supplemented by a detailed single-case failure analysis. The baseline database comprises 79 unique weld cycles drawn from two identical Schlatter units at the plant, designated as Machine BSP1 (Unit 31101) and Machine BSP2 (Unit 31102), as stratified in Table IV.

| Rail Metallurgy Grade | Machine Unit BSP1 | Machine Unit BSP2 | Total Population |
|---|---|---|---|
| R260 Standard Pearlite | 25 | 25 | 50 joints |
| R350HT Head Hardened | 15 | 14 | 29 joints |
| Total Set Size | 40 | 39 | 79 joints |

**TABLE IV: Stratification Layout of the Process Signature Database**

### *B. Feature Extraction Framework*

Each weld cycle is reduced to thirteen scalar descriptors. Seven are recorded directly by the monitoring system; six are derived. The derived features are the analytical contribution of this stage: they express rate and ratio quantities that the raw record does not, and they are dimensionally comparable across rail sections in a way that absolute distances and times are not, as detailed in Table V.

| S No. | Feature Name | Unit | Type | Structural Formula & Physical Derivation |
|---|---|---|---|---|
| 1 | Secondary RMS Current | kA | Logged | Direct raw electrical delivery measurement |
| 2 | Burnoff Time | s | Logged | Duration of initial surface cleaning phase |
| 3 | Burnoff Distance | mm | Logged | Total material consumed during end leveling |
| 4 | Flashing Time | s | Logged | Time window for primary thermal field growth |
| 5 | Flashing Distance | mm | Logged | Material consumed during final flashing phase |
| 6 | Butting Force | kN | Logged | Total force applied to extrude the molten interface |
| 7 | Butting Distance | mm | Logged | Displacement during final consolidation |
| 8 | Linear Flashing Velocity | mm/s | Derived | LFV = Flashing Distance / Flashing Time |
| 9 | Burnoff Velocity | mm/s | Derived | BOV = Burnoff Distance / Burnoff Time |

  

| | | | | |
|---|---|---|---|---|
| 10 | Total Heat Time | s | Derived | t_total = Burnoff Time + Flashing Time |
| 11 | Heat Input Index | kA²·s | Derived | HII = (I_RMS)² * t_total * 10⁻³ |
| 12 | Total Metal Loss | mm | Derived | TML = Burnoff Dist. + Flashing Dist. + Butting Dist. |
| 13 | Upset Ratio | — | Derived | UR = Butting Distance / Flashing Distance |

**TABLE V: Target Feature Extraction and Derived Analytical Equations**

### *C. Replicate Lot Pairing Strategy*

The key methodological step of this work is the construction of a dataset in which a signature record and an independently measured integrity indicator refer to the same weld conditions. Comparison of the two record sets showed that for seven of the ten joints in the macro-examination series, a transverse-load-test record existed for the immediately preceding sequential number on the same machine in the same month. In every one of the seven cases the offset was exactly one, and in every case the rail grade recorded in the two systems agreed. The interpretation is that the two joints of each pair are the consecutive members of a single test lot. They were welded consecutively on the same machine, on the same grade, under the same machine condition and by the same operator. They are therefore process replicates, and the signature record of one may legitimately be associated with the metallurgical measurement of the other.

## V. RESULTS AND DISCUSSION

### *A. Signature Baseline Stratification*

Mean and standard deviation values were calculated across all thirteen parameters for each machine and grade layer, as summarized in Table VI.

| Extracted Parameter Matrix | R260 BSP1 (n=25) | R260 BSP2 (n=25) | R350HT BSP1 (n=15) | R350HT BSP2 (n=14) |
|---|---|---|---|---|
| Secondary Current (kA) | 63.76 ± 2.03 | 65.06 ± 2.04 | 63.47 ± 2.48 | 65.04 ± 3.10 |
| Burnoff Time (s) | 28.84 ± 1.66 | 25.92 ± 2.28 | 27.57 ± 3.29 | 23.65 ± 2.80 |
| Burnoff Distance (mm) | 5.28 ± 0.25 | 6.16 ± 0.23 | 5.28 ± 0.15 | 5.54 ± 0.18 |
| Flashing Time (s) | 13.48 ± 0.59 | 14.05 ± 0.42 | 12.40 ± 0.94 | 14.41 ± 0.83 |
| Flashing Distance (mm) | 11.96 ± 0.73 | 12.32 ± 0.50 | 12.65 ± 0.70 | 12.67 ± 0.98 |
| Butting Force (kN) | 466.39 ± 6.17 | 462.49 ± 2.40 | 562.16 ± 4.76 | 556.21 ± 3.03 |
| Butting Distance (mm) | 14.59 ± 1.30 | 14.43 ± 1.11 | 17.29 ± 1.97 | 16.80 ± 2.43 |
| Linear Flashing Vel. (mm/s) | 0.89 ± 0.07 | 0.88 ± 0.04 | 1.02 ± 0.09 | 0.88 ± 0.09 |
| Burnoff Velocity (mm/s) | 0.18 ± 0.02 | 0.24 ± 0.02 | 0.19 ± 0.03 | 0.24 ± 0.03 |
| Total Heat Time (s) | 42.32 ± 1.91 | 39.96 ± 2.27 | 39.97 ± 3.72 | 38.06 ± 2.68 |
| Heat Input Index (kA²·s) | 171.90 ± 8.73 | 168.93 ± 8.20 | 160.81 ± 14.67 | 160.91 ± 14.13 |

  

| | | | | |
|---|---|---|---|---|
| Total Metal Loss (mm) | 31.83 ± 1.80 | 32.91 ± 1.30 | 35.21 ± 2.52 | 35.01 ± 3.20 |
| Upset Ratio | 1.22 ± 0.08 | 1.17 ± 0.09 | 1.36 ± 0.11 | 1.32 ± 0.13 |

**TABLE VI: Machine-Grade Signature Baselines (Mean ± Standard Deviation)**

### *B. Machine-to-Machine Baseline Divergence Evaluation*

Before the failed joint can be evaluated against control limits, the choice of stratification must be justified. If the two machines produce statistically indistinguishable signature populations, a pooled baseline would be preferable. Table VII reports the comparison using Welch's t-test.

| Grade | Monitored Parameter | Unit BSP1 Mean | Unit BSP2 Mean | Net Shift | Probability (p) | Significant? |
|---|---|---|---|---|---|---|
| R260 | Secondary Current | 63.76 | 65.06 | -1.30 kA | 0.0287 | Yes |
| R260 | Burnoff Time | 28.84 | 25.92 | +2.92 s | <0.0001 | Yes |
| R260 | Burnoff Distance | 5.28 | 6.16 | -0.88 mm | <0.0001 | Yes |
| R260 | Flashing Time | 13.48 | 14.05 | -0.57 s | 0.0003 | Yes |
| R260 | Flashing Distance | 11.96 | 12.32 | -0.36 mm | 0.0464 | Yes |
| R260 | Butting Force | 466.39 | 462.49 | +3.90 kN | 0.0060 | Yes |
| R260 | Butting Distance | 14.59 | 14.43 | +0.16 mm | 0.6338 | No |
| R260 | Linear Flashing Vel. | 0.89 | 0.88 | +0.01 mm/s | 0.4738 | No |
| R260 | Burnoff Velocity | 0.18 | 0.24 | -0.06 mm/s | <0.0001 | Yes |
| R350HT | Secondary Current | 63.47 | 65.04 | -1.57 kA | 0.1467 | No |
| R350HT | Burnoff Time | 27.57 | 23.65 | +3.92 s | 0.0018 | Yes |
| R350HT | Burnoff Distance | 5.28 | 5.54 | -0.26 mm | 0.0003 | Yes |
| R350HT | Flashing Time | 12.40 | 14.41 | -2.01 s | <0.0001 | Yes |
| R350HT | Flashing Distance | 12.65 | 12.67 | -0.02 mm | 0.9388 | No |
| R350HT | Butting Force | 562.16 | 556.21 | +5.95 kN | 0.0005 | Yes |
| R350HT | Butting Distance | 17.29 | 16.80 | +0.49 mm | 0.5607 | No |
| R350HT | Linear Flashing Vel. | 1.02 | 0.88 | +0.14 mm/s | 0.0002 | Yes |

  

| | | | | | | |
|---|---|---|---|---|---|---|
| R350HT | Burnoff Velocity | 0.19 | 0.24 | -0.05 mm/s | 0.0006 | Yes |

**TABLE VII: Machine-to-Machine Variance Analysis via Welch's T-Test**

### *C. Out-of-Sample Sufficiency Testing of the Failed Joint*

The failed joint 06650226BSP2 was welded on machine BSP2 on R260 grade. Its applicable control population is therefore the R260 BSP2 stratum. Table VIII evaluates each of its thirteen scalar features against the control limits derived from that stratum.

| Analyzed Feature Matrix | Lower Limit (μ-3σ) | Population Mean (μ) | Upper Limit (μ+3σ) | Failed Joint Metric | Standard Deviation (Z) | Process Control Verdict |
|---|---|---|---|---|---|---|
| Secondary Current (kA) | 58.93 | 65.06 | 71.19 | 61.30 | -1.84 | Inside Limits |
| Burnoff Time (s) | 19.07 | 25.92 | 32.76 | 29.30 | +1.48 | Inside Limits |
| Burnoff Distance (mm) | 5.47 | 6.16 | 6.86 | 5.80 | -1.58 | Inside Limits |
| Flashing Time (s) | 12.80 | 14.05 | 15.30 | 13.30 | -1.80 | Inside Limits |
| Flashing Distance (mm) | 10.83 | 12.32 | 13.81 | 11.50 | -1.65 | Inside Limits |
| Butting Force (kN) | 455.28 | 462.49 | 469.70 | 463.20 | +0.29 | Inside Limits |
| Butting Distance (mm) | 11.10 | 14.43 | 17.76 | 15.50 | +0.97 | Inside Limits |
| Linear Flashing Vel. (mm/s) | 0.76 | 0.88 | 1.00 | 0.86 | -0.32 | Inside Limits |
| Burnoff Velocity (mm/s) | 0.18 | 0.24 | 0.30 | 0.20 | -2.16 | Warning Flag |
| Total Heat Time (s) | 33.15 | 39.96 | 46.78 | 42.60 | +1.16 | Inside Limits |
| Heat Input Index (kA²·s) | 144.33 | 168.93 | 193.54 | 160.08 | -1.08 | Inside Limits |
| Total Metal Loss (mm) | 29.01 | 32.91 | 36.81 | 32.80 | -0.09 | Inside Limits |
| Upset Ratio | 0.90 | 1.17 | 1.44 | 1.35 | +1.97 | Inside Limits |

**TABLE VIII: Evaluation of Failed Joint Parameters Against Local ±3σ Control Boundaries**

  

### D. Downstream Heat Affected Zone Geometric Performance

Heat affected zone (HAZ) dimensions extracted from the macro-examination records were evaluated across the section profile, as summarized in Table IX.

| Monitored Profile Zone | Mean (mm) | Standard Deviation (mm) | Minimum Observed | Maximum Observed | Net Active Range | One-Sided Cpk (40 mm Limit) |
|---|---|---|---|---|---|---|
| Head Position | 31.07 | 3.25 | 26.2 | 35.2 | 9.0 | 0.92 |
| Web Position | 35.23 | 1.61 | 33.0 | 38.1 | 5.1 | 0.99 |
| Foot Position | 34.75 | 2.39 | 31.3 | 38.7 | 7.4 | 0.73 |

**TABLE IX: HAZ Metric Variations and Process Capability Limits (n=10)**

### E. Signature-to-Integrity Core Correlation Analysis

Pearson product-moment correlation coefficients (r) were computed between the derived process features and independent downstream HAZ width dimensions using the paired replicate dataset, as detailed in Table X.

| Derived Process Feature | HAZ Head Zone | HAZ Web Zone | HAZ Foot Zone |
|---|---|---|---|
| Heat Input Index | +0.368 (0.42) | -0.229 (0.62) | +0.078 (0.87) |
| Total Heat Time | +0.264 (0.57) | +0.450 (0.31) | +0.291 (0.53) |
| Secondary RMS Current | +0.193 (0.68) | -0.445 (0.32) | -0.081 (0.86) |
| Flashing Time | -0.617 (0.14) | -0.431 (0.33) | -0.625 (0.13) |
| Flashing Distance | -0.053 (0.91) | +0.225 (0.63) | +0.203 (0.66) |
| Linear Flashing Velocity | +0.452 (0.31) | +0.455 (0.31) | +0.591 (0.16) |
| Burnoff Time | +0.539 (0.21) | +0.531 (0.22) | +0.560 (0.19) |
| Burnoff Velocity | -0.134 (0.77) | -0.267 (0.56) | -0.241 (0.60) |
| Butting Force | -0.625 (0.13) | -0.196 (0.67) | -0.387 (0.39) |
| Butting Distance | -0.289 (0.53) | -0.174 (0.71) | -0.229 (0.62) |
| Total Metal Loss | -0.124 (0.79) | +0.023 (0.96) | -0.010 (0.98) |
| Upset Ratio | -0.284 (0.54) | -0.388 (0.39) | -0.438 (0.33) |

**TABLE X: Pearson Product-Moment Correlation Matrix (n=7)**

To establish the statistical power of this dataset, an independent power evaluation was conducted using the Fisher z transformation, as summarized in Table XI.

| Target True Correlation Strength (r) | Calculated Power at n=7 | Required Sample Size (n) for 80% Power |
|---|---|---|
| 0.3 | 9.5% | 85 joints |
| 0.4 | 13.5% | 47 joints |

  

| | | |
|---|---|---|
| 0.5 | 19.6% | 30 joints |
| 0.6 | 28.4% | 20 joints |
| 0.7 | 41.1% | 14 joints |
| 0.8 | 59.4% | 10 joints |

**TABLE XI: Statistical Power and Sample Size Requirements (α = 0.05)**

## VI. PROPOSED SOLUTION FRAMEWORK

To address the limitations of standard summary logs, a three-layer diagnostic solution framework has been engineered based on process physics.

### *A. Layer One: Upstream Calibration Gating Rules*

The failure analysis reveals that machinery calibration failures directly precede process degradation. Layer One integrates a strict binary gate into the line control logic: production lines are blocked from starting if any parameter in the calibration routine registers a failure flag. Parameters must be tuned back to their target mid-range values rather than bare compliance. Key metrics, such as the Scaling Travel parameter, must be tracked on rolling trend charts to flag early machinery drift before it impacts joint quality.

### *B. Layer Two: Continuous Intra-Cycle Detection Scheme*

This layer monitors the shape of continuous sensor traces during the active cycle. Real-time alarm rules handle specific mechanical deviations, as detailed in Table XII.

| Rule ID | Monitored Signal | Programmed Real-Time Alarm Threshold | Target Defect Mechanism Addressed |
|---|---|---|---|
| R1 | Platen Speed Profile | Local velocity drops below 40% of command curve for >1.0 s | Localized Flashing Arrest / Initial Sticking |
| R2 | Travel Stagnation | Displacement increment drops below threshold over 1.0 s | Solid Interfacial Contact / Platen Freezing |
| R3 | Current Envelope | Local current deviation rises >10% above moving baseline | Short-Circuit Resistance Collapse |
| R4 | Curve Form Architecture | Splitting of travel trace into distinct multi-regime velocity shapes | Transducer Circuitry Drift / Servo Valve Slip |
| R5 | Burnoff Velocity Log | Extracted summary scalar metric drops below standard Z = -2 | Sluggish Travel Servo Response |
| R6 | Calculated Upset Ratio | Extracted summary scalar metric rises above standard Z = +2 | Viscous, Overheated Interfacial Oxides |

**TABLE XII: Real-Time Intra-Cycle Detection Rules and Physical Mechanisms**

### *C. Layer Three: Machine-Stratified Statistical Process Control*

The final layer applies traditional Shewhart control charts to summary scalar logs using machine-specific and grade-specific limits. While Layer Two cannot detect rapid intra-cycle flashing discontinuities, it tracks long-term machinery drift, utility variations, and lot-to-lot changes in rail-end preparation quality.

## VII. CONCLUSIONS AND FUTURE WORK

  

### *A. Concluding Engineering Summaries*

1) Traditional summary-value process logs are fundamentally blind to defects caused by short-duration flashing discontinuities. A production joint that suffered a brittle fracture under press straightening displayed normal scalar properties, with 12 of its 13 metrics residing within 2σ of the population mean.
2) This limitation stems from the mathematics of data reduction: flashing time and distance function as integrated averages, which smooths out temporary travel plateaus and hides brief current spikes.
3) The root cause of the joint failure was tracked to an unrectified calibration error in the machine's Scaling Travel parameter (7.69 mm/V) one month prior to production, which caused travel control degradation.
4) Nominal process parameters vary significantly between identical machines processing identical rail profiles, proving that raw numerical control thresholds cannot be shared across different installations.
5) While derived process indices correlate with downstream heat affected zone metrics in directions consistent with physics, the dataset requires at least 30 paired joints to achieve the 80% statistical power needed to validate predictive models.

### *B. Technical Recommendations for Future Work*

To complete the validation of the process model, future work should focus on three areas: Vickers Hardness Traverses (execute high-density longitudinal microhardness testing with 1 mm spacing within 25 mm of the fusion line to map out soft zones and link thermal profiles to structural boundaries); Mechanical Testing (conduct transverse tensile and full-section slow bend testing on paired replicates to track how specific trace anomalies change mechanical performance); and Real-Time Control Integration (program the Layer Two detection rules directly into the machine's control software to trigger automatic joint rejections on the line, preventing defective panels from moving downstream).

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