

Influence of High-Temperature Strain Gauge Installation Parameters on Measurement Accuracy and Reliability in Engine Testing

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Abstract. Strain measurement in gas turbine and rocket jet engines at 800–1000°C remains challenging due to temperature-induced drift and instability. While high-temperature strain gauge alloys are well-studied, the influence of mounting process parameters is often underestimated in practice. This paper presents an experimental study of four key mounting parameters: cement layer thickness, surface roughness, heat treatment ramp rate, and flame-spray coating distance. Tests were performed on nichrome (diameter wire 18 μm) and FeCrAl (diameter wire 20, 45, 16.5 μm) gauges up to 950–1000°C. Results show that increasing ramp rates above 10°C/min cause microcracks. For Rokide flame-sprayed coatings, spraying distance below 80 mm causes thermal damage, while distance above 200 mm produces porous coating. Characteristic failure signatures for each violation are identified. Quantitative relationships provided enable error budgeting for high-temperature strain measurement in engine testing.

Keywords: high-temperature strain gauge, ceramic cement, Rokide, flame-sprayed coating, installation parameters, mounting accuracy, resistance drift, engine testing.

1. Introduction

Modern gas turbine and rocket engine testing requires reliable strain measurement on components operating at 800–1000°C. Foil strain gauges with an organic connection have a working temperature of up to 250°C, it is possible to increase the working temperature to 350°C using special glues and additional protection of the place of the outputs to the contact pads with a sealant. High-temperature strain gauges (ceramic-bonded or flame-sprayed) can survive such environments, but their accuracy strongly depends on proper mounting — a factor often underestimated in practice [1,2].

Many studies focus on the strain gauge alloy itself — FeCrAl thin films [3], PtW, PtRh compositions, and TCR compensation methods. However, even the best alloy will produce erroneous data if mounted incorrectly. Existing recommendations (NASA WL-TR-93-3020 [5], NACA TN 4215 [4]) provide general guidelines but lack quantitative relationships between specific installation errors and measurement degradation.

The objective of this study is to experimentally investigate how four controllable mounting parameters affect:

- strain transfer accuracy (error in measured vs. true strain);
- resistance drift over time and thermal cycles;
- characteristic failure signatures for post-test diagnosis.

Two fundamentally different mounting techniques are compared: ceramic cement bonding (used up to 800°C) and Rokide flame-sprayed Al_2O_3 coating (800–1000°C).

2. Experimental Setup

2.1 Test Bench and Procedure

A high-temperature deformation simulator was used (Figure 1). The test protocol included:

- stepwise heating from 25°C to 1000°C (100°C steps);
- dwell time: 12 minutes at each temperature step;
- mechanical loading: $\pm 500 \mu\text{m}/\text{m}$ strain cycles;
- total test duration per specimen: 2–3 hours.



Figure 1 - High-temperature test bench.

2.2 Specimens and Strain Gauges

Parameter	Value
Spring element	Heat-resistant nickel-based alloy EI929
Spring size	560 × 8 × 6 mm
Strain gauge alloys	Wire Nichrome Ø18 μm , FeCrAl Ø20, 45, 16.5 μm
Mounting method (up to 800°C)	Ceramic cement
Mounting method (800–1000°C)	Rokide flame-sprayed Al_2O_3

Surface preparation followed standard practices: degreasing with acetone and isopropanol, then mechanical abrasion or grit blasting to achieve target roughness R_a .

Cement layer thickness was measured after curing using a digital micrometer (accuracy $\pm 0.002 \text{ mm}$) at five points along the gauge grid.

2.3 Investigated Parameters

Four parameters were varied independently while keeping others at baseline recommended values:

Parameter	Range tested	Baseline (optimal)
Cement layer thickness	0.05–0.25 mm	0.08–0.12 mm
Surface roughness R_a (cement)	1–15 μm	1–3 μm
Surface roughness R_a (Rokide)	1–15 μm	4–8 μm
Heat treatment ramp rate	2–20°C/min	$\leq 3^\circ\text{C/min}$
Rokide spraying distance	50–300 mm	100–150 mm

3. Results

3.1 Effect of Cement Layer Thickness

Cement pre-coat was varied from 0.05 to 0.25 mm, measured as described in Section 2.2, results shown in Figure 2.

Key findings are summarized below.

Pre-coat thickness:

- below 0.05 mm leads to poor electrical insulation, quantitative measurement of insulation resistance vs. thickness at high temperature was beyond the scope of this study, but the observed increase in noise and spikes (by a factor of 3–5 compared to optimal thickness) clearly indicates insulation degradation below 0.05 mm.
- 0.08–0.12 mm is the optimal range;
- at 0.20 mm, reduces strain transfer by 27%.

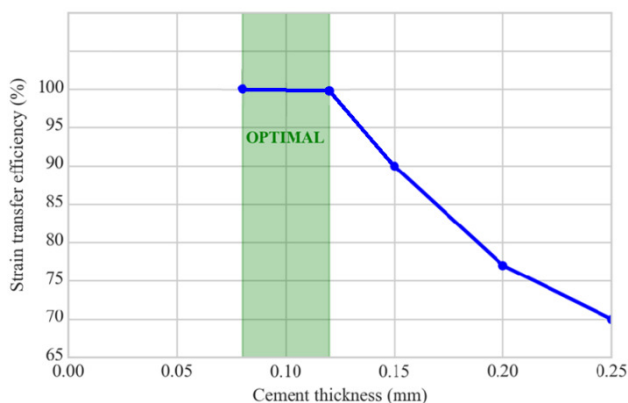


Figure 2 – Strain transfer efficiency as a function of cement layer thickness.

3.2 Effect of Surface Roughness

Two mounting methods showed different roughness requirements.

For ceramic cement, R_a below 1 μm caused delamination after 2–3 thermal cycles.

R_a of 1–3 μm (achieved by sandblasting with 50–100 μm Al_2O_3 powder) provided stable adhesion and is the recommended range.

R_a above 12 μm (e.g., with 250 μm powder) trapped air pockets and increased porosity, leading to drift.

For Rokide flame-sprayed coating, the optimal roughness (R_a 4–8 μm) is higher because the molten Al_2O_3 particles (typical size 10–50 μm) require deeper anchoring sites for mechanical interlocking. Below 3 μm , the coating cannot grip and detaches. Above 8–10 μm , the peaks are not fully wetted by the molten particles, leaving gaps and producing a porous, weakly bonded layer with increased drift. Grit blasting to R_a 4–8 μm was identified as the most critical single factor for Rokide success. Improper surface preparation was the most common cause of coating failure, consistent with NASA findings [5].

3.3 Effect of Heat Treatment Ramp Rate (Ceramic Cement)

Curing ramp rate significantly affected final stability. Tests were performed with final cure temperature 320°C and dwell time of 50 minutes.

Ramp rate $\leq 3^\circ\text{C/min}$ produced stable performance with minimal drift as baseline. In the range between 3°C/min and 10°C/min, the resistance drift increases approximately linearly from near zero to 20–23%. Ramp rate of 10°C/min caused microcracks visible at 50× magnification, with drift increased by 20–23%, as shown in Figure 3. Ramp rate above 15°C/min led to severe cracking and complete signal loss after the first thermal cycle in 40% of specimens.

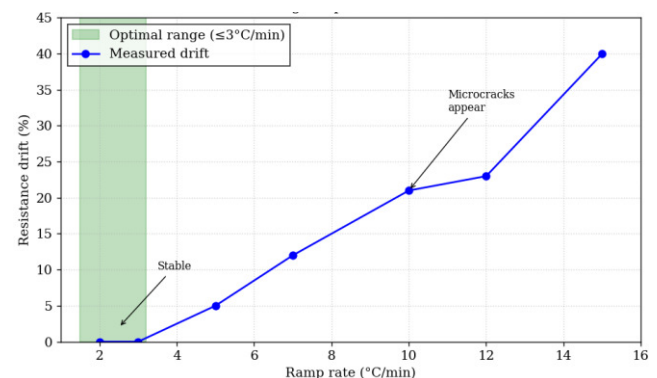


Figure 3. Normalized resistance drift vs. curing ramp rate.

3.4 Effect of Rokide Spraying Distance

Rokide flame-sprayed coating parameters were investigated with Al_2O_3 rod and oxy-acetylene flame. Part temperature was monitored throughout.

Table 1 presents the effect of spraying distance on performance.

Table 1 - Effect of spraying distance on performance.

Distance (mm)	Part temperature (°C)	Drift	Observed failure
70	>250	+22%	Thermal damage
100	~160	0%	None
150	~130	0%	None
200	~100	+29%	Porous coating, poor adhesion, delamination

Above 200	~100	More than +29%	Porous coating, poor adhesion, delamination
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Key findings are as follows.

Distance below 80 mm causes grid temperature to exceed the 200°C limit [9], resulting in permanent resistance increase of 10–20% and gauge destruction:

- oxidation. The nichrome or FeCrAl grid oxidises rapidly, irreversibly increasing resistance by 10–20%. Preferential oxidation of chromium alters the alloy composition;
- thermal shock and differential expansion. Rapid heating/cooling cycles (thermal shocks) induce mechanical stresses in the thin grid wires. Mismatch in coefficient of thermal expansion (CTE) between the grid, the Al₂O₃ coating, and the substrate creates shear stresses at interfaces, leading to microcracks and drift;
- loss of temporary tape adhesion. The PTFE (Teflon) tape that holds the grid in place loses adhesion above ~200 °C. The grid may lift from the substrate before the Rokide coating bonds, distorting its geometry and causing uneven contact.

Distance above 200 mm produces porous coating with drift more than 29% as shown in Figure 4. Effect of forced air cooling: during multi-pass spraying (3–4 passes), the use of vortex cooling directed at the gauge grid was found to be critical. Without cooling, grid temperature at 80 mm exceeded 250 °C after two passes, leading to resistance drift >22%. With active vortex cooling, the grid temperature remained below 200 °C even at 70 mm distance and the resulting drift was comparable to the optimal range (≈3–5%). Due to the limited number of specimens (n=5), these results are preliminary and not included in Table 1. A dedicated study of cooling parameters is recommended for future work.

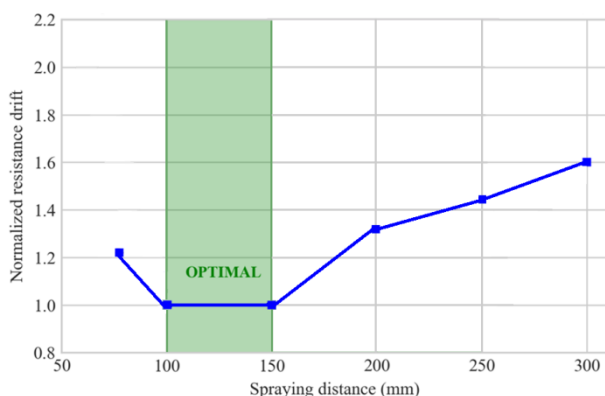


Figure 4 – Normalized resistance drift vs. spraying distance.

3.5 Silicone Contamination

Temporary tape carriers used during installation often contain silicone adhesives. Testing confirmed that silicone contamination cannot be removed by solvents alone as reported in [5]. It causes poor adhesion and voids. Baking at 427°C (800°F) for 2 hours converts silicone to non-detrimental silica powder. White powder on the surface after high-temperature bake is normal silica and does not indicate failure.

To minimise the risk of silicone contamination, additional protective measures can be employed. These include applying a second layer of tape over the carrier to create a barrier, or using metal stencils instead of adhesive tapes for grid positioning. Such methods physically isolate the gauge from silicone residues and are particularly beneficial when high-temperature baking is impractical due to component size or assembly constraints.

3.6 Failure Signatures in Test Data

Characteristic patterns were identified enabling post-test diagnosis (Table 2).

Table 2 - Post-test diagnosis.

Observed signature	Most likely cause
Sudden jump in signal followed by gradual decay	Delamination (poor adhesion, wrong surface roughness, or contaminated surface)
Steadily decreasing zero reading	Incomplete curing (temperature too low or time too short)
Strain reading 20–30% below expected	Excessive cement thickness
Complete signal loss after first thermal cycle	Very thin cement layer (<0.05 mm) → poor insulation
High noise, random spikes, unstable zero	Silicone converted to silica (normal, not a failure)
Porous, flaky coating; high drift	Surface not degreased (oil, grease, fingerprints)
Delamination or blistering after curing	Moisture during cement or Rokide application (humidity >60%)
Poor adhesion, voids, local detachments	Surface not degreased (oil, grease, fingerprints)

4. Discussion

4.1 Comparison with Literature

Our optimal cement thickness of 0.08–0.12 mm agrees with NACA TN 4215 [4] which specifies 0.05–0.15 mm and with Hitec recommendations [7] which specify less than 0.25 mm with grid outline visible. The observed sensitivity of drift to ramp rate quantifies earlier qualitative warnings from NASA [5].

For Rokide, NASA [5] emphasized surface preparation and grid temperature limits. Our results show that spraying distance is equally critical. The recommended distance of 100–150 mm is optimal.

4.2 Physical Interpretation

Strain attenuation with thick cement occurs because the soft ceramic layer deforms elastically, absorbing part of the substrate strain before it reaches the gauge grid. The thicker the layer, the larger the parasitic deformation. Conversely, a very thin cement layer (<0.05 mm) fails to provide adequate electrical insulation. The discontinuous or porous layer allows parasitic currents and capacitive coupling, resulting in high noise, spikes, and risk of electrical breakdown at elevated temperatures.

The ramp rate effect is attributed to thermal gradients that cause differential expansion between the cement, the gauge, and the substrate. At heating rates above 10 °C/min, local stresses exceed the green strength of the uncured cement, producing microcracks that never heal during the final cure.

The Rokide spraying distance involves a trade-off. When the distance is too short (<80 mm), the grid overheats, leading to oxidation, thermal shock, and loss of temporary tape adhesion – all contributing to permanent resistance increase and drift. When the distance is too long (>200 mm), the molten Al₂O₃ particles cool below their melting point before impact, resulting in a porous, weakly bonded coating. Surface roughness affects adhesion through mechanical interlocking. Very smooth surfaces provide no grip, leading to delamination. Very rough surfaces trap air (for cement) or prevent full wetting by molten particles (for Rokide), creating voids and porosity. The optimal roughness range balances these effects and differs between the two methods because of the different scale and state (paste vs. molten droplets) of the bonding medium.

4.3 Practical Implications for Engine Testing

The results provide quantitative error bounds. Thickness error of ±0.05 mm leads to strain error of 10%. Spraying distance error of 200 mm instead of 120 mm leads to drift increase of +29%. These can be used in measurement uncertainty budgets, a practice rarely done for mounting-related errors.

4.4 Limitations

This study has several limitations. Only nichrome, FeCrAl and PtW8 alloys were tested. Maximum of 10 thermal cycles was applied; long-term drift beyond 10 hours was not evaluated. Only two cement formulation and one Rokide rod composition (Al₂O₃) were used. These limitations will be addressed in future work.

5. Conclusions

Cement pre-coat thickness is the most critical parameter for ceramic-bonded gauges. Keep it within 0.08–0.12 mm. Deviation beyond this range rapidly degrades accuracy, reaching 27% error at 0.20 mm.

Surface roughness requirements differ by method. R_a of 1–3 µm is required for ceramic cement. R_a of 4–8 µm is required for Rokide. Grit blasting is mandatory for Rokide; smooth surfaces cause delamination within 2–3 cycles.

Heat treatment ramp rate must not exceed 3°C/min. Cure temperature must be 320°C.

Rokide spraying distance must be maintained within 100–150 mm.

Silicone contamination from tape carriers cannot be removed by solvents; baking at 427°C for 2 hours is required.

Characteristic failure signatures including sudden jumps, progressive drift, strain attenuation, and high noise enable post-test diagnosis of mounting quality.

Quantitative relationships provided in this paper allow integration of mounting-induced errors into measurement uncertainty budgets for engine testing applications.

6. References

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