

High Temperature Investigation of Polymer-Free Strain Gauges for Integration in DED-LB Components

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Summary:

Strain gauges integrated into additively manufactured metal components allow precise internal strain measurement for lifetime prediction. To withstand process temperatures up to 1,200 °C, thin-film sensors were fabricated on stainless steel substrates. After annealing, insulation maintained sufficient dielectric strength. The k-factor of the sensor doubled to 2.3, while resistance dropped by 50% and TCR remained constant up to 800 °C. The diffusion barriers prevented diffusion up to at least 800 °C. These results confirm the suitability of thin-film strain gauges for sensor integration in DED-LB components.

Keywords: high-temperature, thin-film, strain gauges, insulation layer, diffusion barrier

Introduction

Sensors are essential in industrial applications for real-time monitoring and predictive maintenance. Integrating sensors directly into components using additive manufacturing, particularly Laser Based - Directed Energy Deposition (DED-LB), offers unique advantages as the layer-by-layer process allows the precise placement of sensors in the component that are inaccessible via conventional methods, but requires the development of high-temperature-resistant sensor systems [1]. Previous integration methods often relied on robust and bulky encapsulations and used different methods like Laser Powder Bed Fusion [2]. This work aims to investigate thin-film strain gauges suitable for DED-LB integration, focusing on using high process temperatures for sensor annealing rather than shielding. The study analyzes the sensor system's k-factor, temperature coefficient of resistance (TCR), resistivity, the insulation's dielectric strength and resistivity and diffusion behavior before and after annealing.

Manufacturing and Annealing of the Sensor

All strain gauges were fabricated on 800 µm thick stainless steel (1.4301) substrates, chosen for future integration into machine tool components using DED-LB. The use of stainless steel ensures a strong bond and efficient transfer of strain between the sensor and the component. Substrate surface roughness was measured at $R_a = 31 \pm 3$ nm and $R_z = 842 \pm 143$ nm. A schematic of the manufactured sensor is shown in Fig. 1a. Al_2O_3 was used as insulation material (2 µm) due to its excellent high-temperature

insulating properties and its thermal expansion compatibility with both substrate and sensor materials. Tantalum (Ta) was applied as a diffusion barrier (0.2 µm) between the sensor and insulation layers, providing thermal stability and good adhesion. NiCr (50/50 wt.%) was used as sensor layer (0.4 µm) due to its linear k-factor, low TCR, and high-temperature stability. A gold layer was deposited as protective layer on the contact pads (0.5 µm) for reliable electrical contact after annealing. All layers were deposited by sputtering. The fabricated sensors were separated into 1.5×1.5 cm chips and annealed at 600 °C, 800 °C, and 1,200 °C (Fig. 1b) in a ceramic oven for 60 s in ambient atmosphere, simulating the short-term thermal loads typical in DED-LB. Three samples per temperature were analyzed and were cooled to room temperature post-annealing. Temperature choices were based on prior heat simulations of DED-LB processes [1].

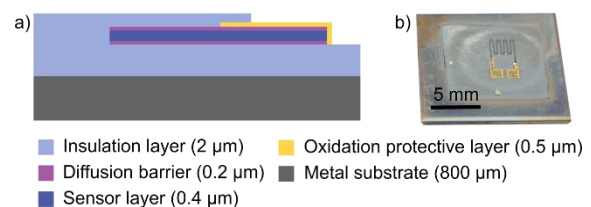


Fig. 1. a) Schematic of the integrable strain gauge system, b) strain gauge annealed at 1,200 °C

Electrical and mechanical characterization

The electrical resistivity ρ and dielectric strength E of the insulation layer were evaluated before and after annealing. A significant increase in ρ and E was observed after annealing at 800 °C.

Tab. 1: Electrical and mechanical characterization of insulation and sensor layer

Properties		As-deposited	600 °C	800 °C	1,200 °C
Al ₂ O ₃	ρ [Ωcm]	$1.35 \cdot 10^{11} \pm 4.08 \cdot 10^{10}$	$2.06 \cdot 10^{11} \pm 8.81 \cdot 10^{10}$	$1.03 \cdot 10^{14} \pm 5.16 \cdot 10^{13}$	$7.71 \cdot 10^8 \pm 3.13 \cdot 10^8$
	E [kV/mm]	40.00 ± 4.7	39.38 ± 2.7	76.25 ± 26.7	46.25 ± 5.9
Sensor	$\Delta R/R$ [%]	-	1.0 ± 0.8	-2.4 ± 1.2	-58.3 ± 1.6
	k [-]	1.1 ± 0.1	1.4 ± 0.2	1.8 ± 0.1	2.3 ± 0.1
	TCR [ppm/°C]	21.9 ± 0.3	51.7 ± 0.8	40.4 ± 4.5	1237.2 ± 53.9

This may be caused by phase transformations of Al₂O₃ to γ -Al₂O₃ at 800 °C and δ - θ -Al₂O₃ at 1,200 °C [3]. Additionally, at 1,200 °C, cracks and delamination in the thin-film insulation are clearly observable, which explains the significant drop in resistivity. All samples still retained functional insulation, confirming their suitability for integration via DED-LB. The effectiveness of the diffusion barrier was examined through XPS analysis. For temperatures up to 800 °C (Fig. 2), the Ta barrier successfully prevented inter-diffusion. However, at 1,200 °C, XPS could no longer distinguish clear separations between layers, which seems to be due to loss of layer adhesion, rather than interdiffusion. Furthermore, XPS data revealed a NiCr concentration of 40:60 at.% (43:57 wt.%), which deviates from the nominal 50:50 wt.% ratio and could indicate local alloy variations after annealing.

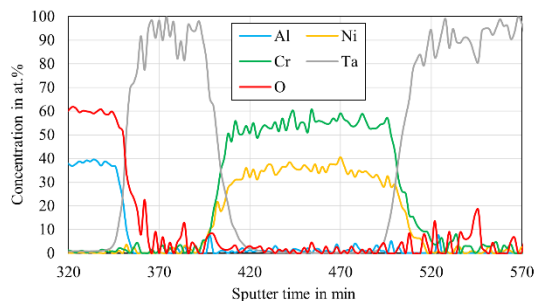


Fig. 2. XPS analysis for a sensor system after 60 s annealing at 800 °C.

Strain gauge resistance R was measured at room temperature before and after annealing. Only minor resistance changes occurred, except after annealing at 1,200 °C, where resistance decreased by about 58%. This reduction is likely caused by annealing-induced reduction of lattice and point defects in the NiCr thin-film, leading to lower resistivity. The k -factor k was characterized through cyclic tensile tests, with strain measured up to 208 $\mu\text{m}/\text{m}$. Annealing at higher temperatures caused significant increases of up to 217%. This is comparable to literature values for NiCr thin films ($k = 2.3$) and Ta thin films ($k = 2.8$) and exceeds values for commercial strain gauges typically around $2.0 \pm 1\%$ in a

temperature range of only -269 °C to +250 °C [4]. The increase is attributed to relaxation of residual stresses and possible phase separation in the NiCr layer (formation of Ni-rich and NiCr regions), as expected from the phase diagram and supported by XPS-measured concentration gradients. TCR measurements revealed a sharp increase by a factor of 30 after annealing at 1,200 °C. This change is likely related to the same phase transformations and microstructural reorganization responsible for the increase in k -factor. A low TCR is preferred for strain gauges to ensure minimal thermal drift and noise; literature typically cites values below 200 ppm/°C for NiCr (50/50 wt.%) and Ta, a criterion met by all except the samples annealed at 1,200 °C. Nevertheless, the higher-TCR samples remain suitable for temperature-stable strain gauge applications. These results confirm the suitability of thin-film strain gauges for sensor-integrated components in additive manufacturing, with further studies recommended to optimize layer adhesion and investigate phase transformations.

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