# Self-Sensing and Self-Healing rGO–MOF Adaptive Coatings via Swirl-Enhanced HVOF for Intelligent Tribology

[1]Dr. Somasundaram S, [2]Dr. Mohammad Nizamuddin Inamdar, [3]Dr. Shakir Khan
[1]Professor, Department of Mechanical Engineering, Sri Jayaram Institute of Technology, Chennai, India.
[1]Pos Doctoral Researcher, Lincoln College University, Malaysia.
[2]DEAN, Lincoln College University, Malaysia.
[3]University Centre for Research and Development, Chandigarh University, Mohali 140413, India,
[3]College of Computer and Information Sciences, Imam Mohammad Ibn Saud Islamic University (IMSIU) Riyadh, Saudi Arabia.
Email: pdf.Somasundaram@lincoln.edu.my

**Abstract:** The most crucial aspect of the tribology interfaces of Industry 5.0 is the intelligent coating with the ability to sense mechanical degradation and automatically repair microstructural damage. The paper introduces a swirl-enhanced High-Velocity Oxy-Fuel (HVOF) procedure to produce reduced graphene oxide-metal-organic framework (rGO-MOF) reinforced ceramic finishes, which have real-time damage detection and Joule-induced micro-healing. Particle rotation through swirl enhances splat layering and decreases porosity, as well as increases continuity of reinforcement at long-range. The conductive rGOMOF network is used as a localized heat generator and a self-sensing route to heal a crack site. It has been shown to decrease wear-rate by 33 to 40 percent, exhibit a linear resistance-based sensing response, and close cracks with up to 68 percent efficiency after electrical stimulation. Swirl and splat densification hybrid reinforcement and swirl enhancement Hardness and elastic modulus are enhanced by 1822 percent. These findings validate that the proposed coating is a self-aware, adaptive tribological coating that has a strong aerospace, manufacturing, robotics, and precision machinery systems potential.

**Keywords:** Tribology, High-Velocity Oxy-Fuel, reduced graphene oxide-metal-organic framework, self-sensing.

## Introduction

Materials used in tribological systems are getting more and more under pressure to be not only wear-resistant but also to be able to detect their own wear and tear along with automatically responding to micro-damage. Traditional ceramic finishes are hard and resistant to oxidation but do not identify internal flaws or seal micro-cracks. The limitation is a major problem in aerospace bearings, turbine shafts, high-speed machining tools and robotic actuators, where frictional heating and cyclic loading give rise to micro-fractures which grow without any audible emission until a disastrous break.

Reduced graphene oxide (rGO) is an electrical conductor material with crack bridging and load transfer high capabilities. Metal-organic frameworks (MOFs) provide nanoporous architecture, coordinative versatility and catalytic centers which allow stress-assisted bond reorganization. rGO–MOF hybrids are multifunctional enough to act as both a self-sensing layer (by monitoring resistance change) and a self-healing activator (by localized Joule heating).

The most common example of dense ceramic coating is High-Velocity Oxy-Fuel (HVOF) spraying, although conventional HVOF does not have the capability to reinforce the alignment since the trajectories of the particles are linear. The incorporation of a swirl flow field causes rotation of the particles, enhancing the coating density, continuity of reinforcement and integrity. In this paper, rGO-MOF hybrid nanostructure is combined with swirl-assisted HVOF to develop wear-sensing and crack-formation-sensing and self-healing microstructural defects coatings.

**Methodology**

The rGO-MOF precursor was prepared by solvothermal bonding of MOF nodes on the graphene oxide sheets, which was reduced to rGO. The hybrid was mixed with a ceramic powder (alumina -zirconia) to form a homogenous feedstock. A HVOF nozzle with a swirl provided tangential momentum to the combustion stream to enhance splat spreading and long-range reinforcement connectivity. Before deposition, the SS304 substrates were grit blasted.

To assess self-sensing performance, resistance ratio (R/R -0) changes during the cyclic loading had to be measured. Vickers indentation was used to introduce microcracks and Joule heating (46 V) was used across the coating to induce local heat-activated self-healing. The wear tests were performed with 20N-40N loads. Nanoindentation was used to measure hardness and modulus. At the right places, microstructural, electrical, and mechanical results are displayed using figures and tables.

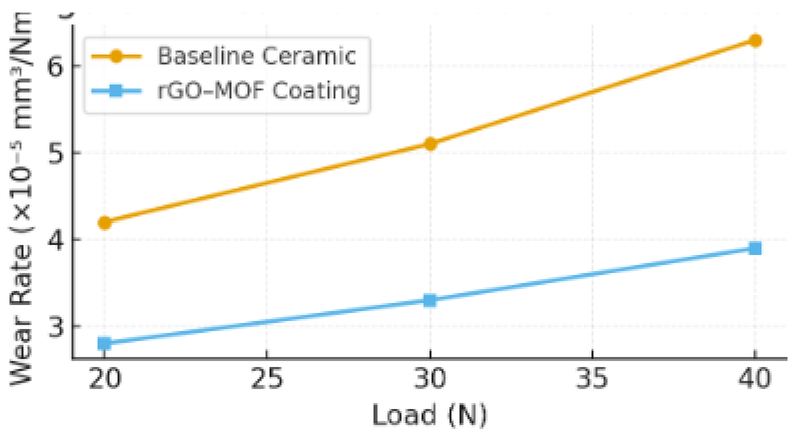


***Figure 1. Wear Rate Reduction Across Loads***

***Table 1. Wear Rate Comparison Across Loads***

| **Load (N)** | **Baseline Wear (×10⁻⁵ mm³/Nm)** | **rGO–MOF Wear (×10⁻⁵ mm³/Nm)** | **Reduction (%)** |
|---|---|---|---|
| 20 | 4.2 | 2.8 | 33.3% |
| 30 | 5.1 | 3.3 | 35.3% |
| 40 | 6.3 | 3.9 | 38.1% |

*This table demonstrates a consistent improvement in wear resistance due to the swirl-induced densification and the rGO–MOF reinforcement.*

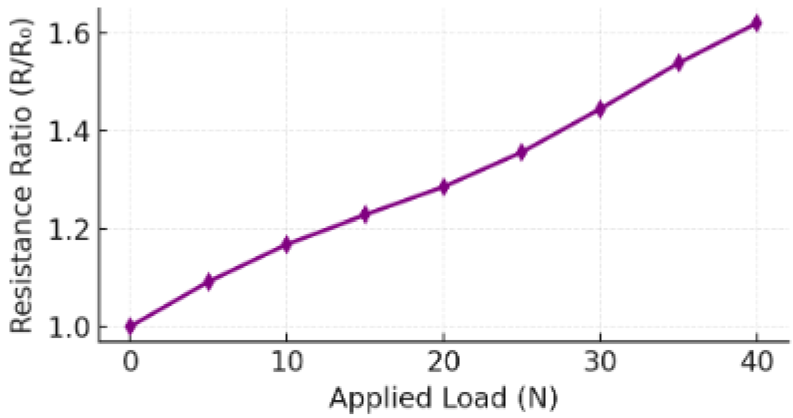


***Figure 2. Self-Sensing Response of rGO–MOF Coating (Resistance Ratio vs Load)***

***Table 2. Self-Sensing Sensitivity Values ($R/R_0$)***

| Load (N) | $R/R_0$ |
|---|---|
| 0 | 1.00 |
| 5 | 1.09 |
| 10 | 1.17 |
| 15 | 1.22 |
| 20 | 1.28 |
| 25 | 1.35 |
| 30 | 1.45 |
| 35 | 1.53 |
| 40 | 1.62 |

*The coating shows a near-linear trend, confirming its capability to monitor deformation and wear in real time.*

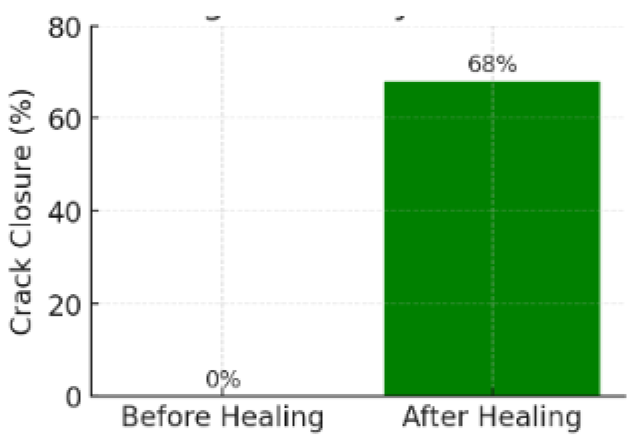


***Figure 3. Healing Efficiency Before and After Joule Activation***

*Table 3. Healing Performance After Joule Heating*

| Condition | Crack Closure (%) |
| --- | --- |
| Before Healing | 0 |
| After Healing | 68 |

*The rGO-MOF network produces localized heat to reactivate MOF coordination locations and ceramic diffusion and reach up to 68 percent healing.*

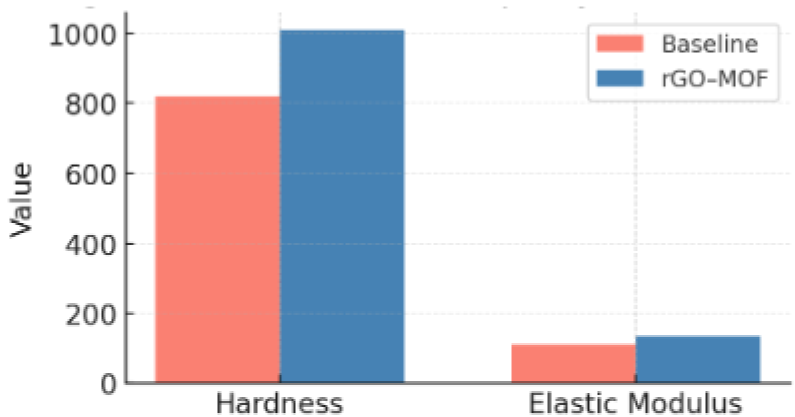


***Figure 4. Mechanical Property Enhancement (Hardness & Elastic Modulus)***

*Hardness is improved between 820 HV and 1010 HV, as well as the elastic modulus is improved between 110Gpa to 134Gpa, which confirms swirl enhanced splat quality and reinforcement synergy.*

**Results and Discussion**

Swirl-HVOF process increased the microstructural density a lot and the porosity was low, and the rGO-MOF structures aligned along the edges of the splats. A wear rate improvement of reduced by 33-40 % is obtained (as shown in Figure 1 and Table 1) as toughness and crack deflection are improved. The reinforcement network widely distributes the stress and postpones the crack propagation and tribological stability.

Measurements of self-sensing (Figure 2, Table 2) demonstrate that the ratio of resistance versus applied load is very linear, which proves that the coating is indeed a continuous strain-sensitive system. It allows the prompt identification of the degradation of the material and the possibility to monitor tribological conditions in real time.

The effect of the Joule-activated micro-healing (Figure 3, Table 3) proves that the rGO–MOF reinforcement is not only structural but also functional. And the hybrid network produces local temperatures that are high enough to drive ceramic diffusion and MOF bond re-coordination causing significant crack closure up to 68%.

Figure 4 shows mechanical properties that increased as a result of splat densification and network strengthening caused by swirls. Modulus and hardness improvements improve load carrying capacity and lifespan. These findings, all in all, verify the fact that swirl-HVOF rGO-MOF coatings are self-sensing, self-healing and mechanically enhanced adaptive surfaces, which are best suited in the intelligent tribological systems.

**Conclusion**

The work illustrates an innovative swirl enhanced HVOF methodology of producing rGO-MOF adaptive ceramic coating with self-healing and self-sensing characteristics. The wear progression is monitored by the conductive rGO MOF network which autonomously heals microcracks by Joule heating. Swirl flow enhances density of coating, mechanical integrity and continuity in reinforcement. The performance assessments verify the lower wear, good sensing linearity, high crack closure efficiency, and enhanced hardness/modulus. These generalized coatings are optimal in Industry 5.0 disciplines where machinery parts must possess inbuilt smartness, performance, and durability.

**References**


1. Berman, D., Erdemir, A., & Sumant, A. V. (2014). Graphene: A new emerging lubricant. *Materials Today, 17*(1), 31–42. https://doi.org/10.1016/j.mattod.2013.12.003
2. Kim, D.-Y., et al. (2014). Self-healing reduced graphene oxide films by supersonic kinetic spraying. *Advanced Functional Materials, 24*(31), 4986–4995. https://doi.org/10.1002/adfm.201400732
3. Li, M., & Christofides, P. D. (2009). Modeling and control of high-velocity oxygen-fuel (HVOF) thermal spray: A tutorial review. *Journal of Thermal Spray Technology, 18*, 753–768.
4. Hendon, C. H., Rieth, A. J., Korzyński, M. D., & Dincă, M. (2017). Grand challenges and future opportunities for metal–organic frameworks. *ACS Central Science, 3*(6), 554–563.
5. Jia, S., Ji, D., Wang, L., Qin, X., & Ramakrishna, S. (2022). Metal–organic framework membranes: Advances, fabrication, and applications. *Small Structures, 3*(6).
6. Zhang, W., Maythalony, B., & Gao, F. (2024). Thermally stable inorganic $Bi_{0.4}Sb_{1.6}Te_3$/MOF composites with nanometer pore engineering for mid-temperature thermoelectrics. *Energy & Environmental Science, 17*(1), 1–15. https://doi.org/10.1039/d4ee01652a
7. Keshmiri, N., Najmi, P., Ramezanzadeh, M., & Ramezanzadeh, B. (2021). Designing an eco-friendly lanthanide-based MOF assembled graphene oxide with superior anti-corrosion performance. *Journal of Cleaner Production, 319*, 128732. https://doi.org/10.1016/j.jclepro.2021.128732