

IMPROVING WEAR RESISTANCE OF ARC-SPRAYED AlMg COATINGS THROUGH SEALING WITH NANO-SiO₂ MODIFIED EPOXY

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Abstract - This research paper investigates the improvement of wear resistance of arc-sprayed AlMg alloy coatings through epoxy impregnation treatment containing silica (SiO₂) nanoparticles. Experimentally, the effect of different SiO₂ nanoparticle concentrations on the friction-wear properties of the coatings was examined. Wear behavior was evaluated by a ball-on-flat reciprocating abrasion test conducted on a UMT-3MT tribometer in accordance with ASTM G133. The effects of nano SiO₂ concentration on wear depth, friction coefficient, and wear rate were systematically analyzed. The results indicate that, epoxy sealing significantly enhances the wear resistance of AlMg coatings, while the incorporation of nano SiO₂ further improves this effect. An optimal nano SiO₂ content of 2 wt.% was identified, at which the coating exhibited the lowest wear depth, friction coefficient, and wear rate, demonstrating the effectiveness of nanosilica-modified epoxy sealing.

Key words - Pray coating; sealing; nano SiO₂; wear resistant; AlMg alloy

1. Introduction

AlMg alloy coatings produced by electric arc thermal spraying are widely employed in engineering applications, particularly in marine environments, owing to their low density, excellent corrosion resistance, and environmentally friendly characteristics. However, the lamellar structure inherent to thermal spray coatings leads to the presence of pores and microcracks, which adversely affect their mechanical and tribological properties. The porosity of thermal spray coatings typically ranges from 1% to 20%, depending on the spraying technique and processing parameters. In particular, arc-sprayed AlMg coatings exhibit relatively high porosity (approximately 10–20%) and low hardness (64–80 HV0.1), resulting in premature failure when exposed to combined corrosive and abrasive environments [1, 2]. To address these limitations, post-treatment methods aimed at reducing porosity, sealing microcracks, and improving coating hardness have been extensively investigated [3, 4]. These methods include metal-organic chemical vapor deposition [1], heat treatment [5, 6], and various chemical infiltration or sealing techniques [7-12],... Among them, epoxy-based sealing treatments incorporating nanoscale fillers have attracted considerable attention due to their ability to penetrate coating pores and improve mechanical, thermal, and protective properties [13].

Due to their nanoscale size, nanoparticles exhibit a large specific surface area, which promotes strong interfacial bonding with polymer matrices and leads to notable improvements in epoxy performance. Previous

studies have reported that the incorporation of nanoparticles such as Al₂O₃, TiO₂, SiO₂, and CaCO₃ enhances the mechanical strength, modulus, and durability of epoxy coatings [14-16]. When properly formulated, nanoparticle-filled epoxy can effectively infiltrate the porous structure of thermal spray coatings, thereby preventing the ingress of corrosive media and mitigating abrasive damage. Z. Liu et al. demonstrated that epoxy penetrant TiN coatings with TiO₂ nanoparticles have better corrosion resistance than epoxy penetrant TiN coatings without nanoparticles and non-epoxy penetrant TiN coatings. TiO₂ nanoparticles also contribute to increasing the adhesion strength of epoxy and TiN coatings [17].

Among various nanofillers, nanosilica (SiO₂) is particularly attractive due to its low density, high thermal and mechanical stability, and chemical inertness. Several studies have demonstrated that nanosilica-modified epoxy coatings exhibit enhanced hardness, thermal stability, impact resistance, and corrosion protection [18-21]. According to research by H. L. H. Cuong et al., epoxy coatings dispersed with 1% nano SiO₂ have significantly higher heat resistance and impact strength compared to epoxy coatings without nano SiO₂ dispersion (from 5 kg x cm to 57.5 kg x cm) [18]. In 2012, A. Allahverdi et al. showed that the hardness and elastic modulus of an epoxy coating containing 5% nano SiO₂ increased by 26% and 21%, respectively, compared to an epoxy coating without nano SiO₂ [20]. M. Conradi et al. also presented research results showing that SiO₂ nanoparticles with a size of 130 nm and a concentration of 2%, dispersed in an epoxy coating on a stainless steel substrate, significantly improved the hardness (increased by approximately 40%), surface roughness, and hydrophobicity of the coating [21]. However, despite extensive research on the mechanical and anticorrosion performance of nanosilica-filled epoxy systems, quantitative investigations into their effect on the wear resistance of sealed thermal spray coatings remain limited.

Therefore, the present study aims to evaluate the influence of epoxy sealing containing different concentrations of nanosilica on the tribological behavior of arc-sprayed AlMg coatings. The optimal nanosilica content for maximizing wear resistance is systematically determined through standardized abrasion testing.

2. Materials and experimental methods

2.1. Materials and coating preparation

Carbon steel substrates with dimensions of $50 \times 50 \times 3$ mm were used in this study. An AlMg alloy coating with a thickness of 300 ± 25 μm was deposited onto the substrate surface using an electric arc thermal spraying process. The spraying parameters are listed in Table 1 [22]:

Table 1. The spraying parameters

No.	Parameters	Value
1	Arc voltage, V	32
2	Spray current, A	300
3	Air pressure, bar	5.5
4	Spray distance, mm	160
5	Spray angle ($^\circ$)	90

Bisphenol A-based epoxy resin with an epoxy equivalent of 205–225 g/eq and a viscosity of 19,000–24,000 cps at 25°C was used as the sealing material. A polyamide curing agent with an amine equivalent of 140 g/eq was employed. Nanosilica (SiO_2) particles with a purity of $\geq 99.9\%$ and particle size of 10–15 nm were used as the reinforcing filler.



Figure 1. AlMg spray coating samples

2.2. Dispersion of nanosilica in epoxy

Prior to dispersion, nanosilica particles were dried at 100°C for 24 h and stored in a desiccator [23]. The epoxy resin was diluted with acetone, surfactant, and a degassing agent and stirred until a homogeneous solution was obtained. Nanosilica was then added at concentrations of 0.5, 1, 2, and 3 wt.% relative to the epoxy resin. The mixture was ultrasonicated at $70\text{--}80^\circ\text{C}$ for 2 h, followed by magnetic stirring at 1000 rpm at room temperature for 45 minutes to ensure uniform dispersion. Subsequently, the curing agent was added at an epoxy-to-curing-agent weight ratio of 1:1, and the mixture was stirred for 30 min [24]. The prepared solution was used within 1 h.

2.3. Sealing treatment

Epoxy sealing of the AlMg coatings was performed using an ultrasonic-assisted impregnation method. The coated samples were fully immersed in the epoxy/nanosilica mixture and subjected to ultrasonic vibration at a frequency of 20–50 kHz for 3–6 h at room temperature. After impregnation, the samples were cured in a drying chamber following a stepped heat-treatment schedule: heating from room temperature to 121°C over 30 min and holding for 2 h, followed by heating to 177°C over 30 min and holding for an additional 2 h. The

samples were then cooled to room temperature inside the chamber [25, 26].

The designations of the coating samples and their corresponding nanosilica contents are listed in Table 2.

Table 2. Symbols for epoxy/nano SiO_2 penetration coating samples

Model name	Nano SiO_2 content (%)
AM-E	0
AM-E0,5S	0.5
AM-E1S	1
AM-E2S	2
AM-E3S	3

2.4. Abrasion test

Wear tests were conducted in accordance with ASTM G133 using a UMT-3MT reciprocating tribometer in Figure 2 [27]. A stainless steel ball with a radius of 4.76 mm and a hardness of 62 HRC was used as the counterbody. The test parameters are summarized in Table 3. Wear resistance was evaluated based on wear depth, friction coefficient, and wear rate.

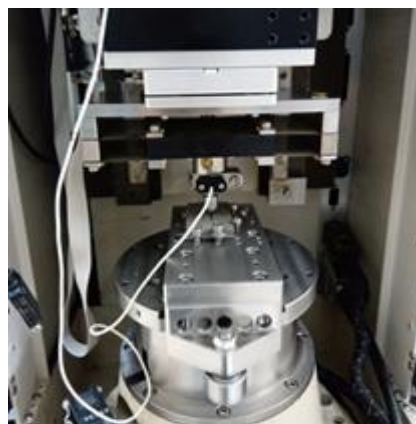


Figure 1. Wear measurement on UMT-3MT device (CETR-USA)

Table 3. Wear measurement regime according to ASTM G133

Ball radius (mm)	Force (N)	Time (s)	Stroke length (mm)	Frequency (Hz)	Temperature ($^\circ\text{C}$)	Relative humidity (%)
4.76	25	990	10	5	22 ± 3	$40 \div 60$

2.5. Analytical methods

The coating's surface features were analyzed employing a scanning electron microscope integrated with an energy-dispersive spectroscopy system (SM-6510LV, Japan).

3. Results and discussion

3.1. Microstructure

Figure 3 presents the surface morphology of the samples observed at $\times 5000$ magnification.

The micrographs show that the as-sprayed AM coating exhibits a highly rough surface with numerous pores and defects. In contrast, the surfaces of the epoxy-impregnated coatings containing nano SiO_2 are completely covered by the epoxy layer, and the previously observed open pores and cracks are no longer visible.

Among all tested coatings, the AM-E2S coating exhibits a relatively more uniform surface morphology compared to the other coatings. For the AM-E0.5S coating, the presence

of small surface pores is observed, which may be attributed to air bubbles entrapped in the epoxy during impregnation and subsequently forming pores on the epoxy surface upon curing. In the case of the AM-E3S coating, a considerable number of large nanoparticle agglomerates are observed on the coating surface. This behavior is attributed to the inherent tendency of nanoparticles to agglomerate; therefore, at higher nano SiO₂ contents, particle aggregation occurs, resulting in non-uniform dispersion within the epoxy during both the dispersion and sealing processes.

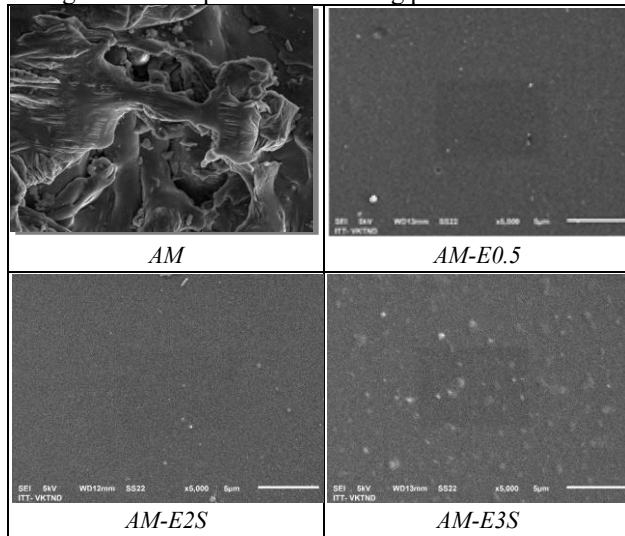


Figure 3. Surface morphology of AlMg/epoxy-SiO₂ coatings

3.2. Wear resistance

The wear depth and friction coefficient were used as primary indicators of the abrasion resistance of the coatings. Lower values correspond to improved wear performance. The results reveal that all epoxy-sealed coatings exhibit reduced wear depth and friction coefficient compared to the unsealed AlMg coating, confirming the effectiveness of epoxy impregnation. The abrasion resistance test results of the coatings are shown in Figures 4 and 5.

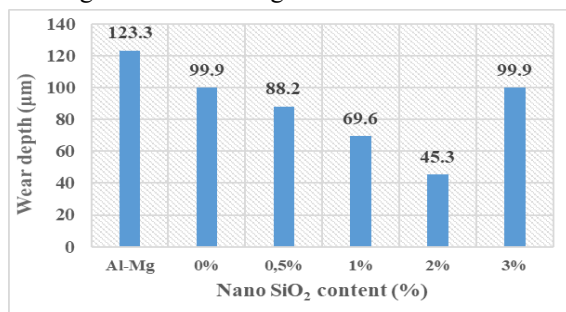


Figure 4. Abrasive depth diagram of AlMg and AlMg/epoxy-SiO₂ coatings

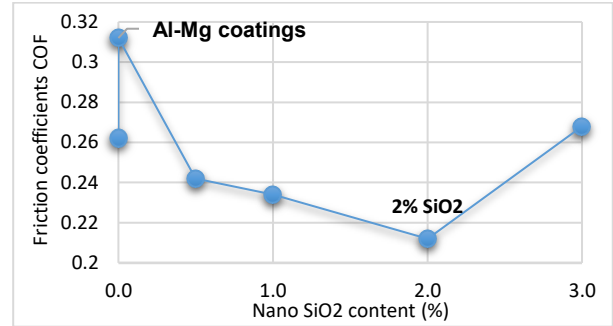


Figure 5. Friction coefficients of AlMg and AlMg/epoxy-SiO₂ coatings

The results indicate that epoxy coatings containing nano-sized SiO₂ particles exhibit significantly improved wear resistance compared with neat epoxy coatings without nano SiO₂. This enhancement can be attributed to the fact that nano SiO₂ particles possess substantially higher hardness and elastic modulus than the epoxy matrix. When uniformly dispersed within the epoxy, the nanoparticles act as effective load-bearing sites in the matrix. Under abrasive contact, the applied stresses are therefore not concentrated in the softer epoxy phase but are redistributed to the nano SiO₂ particles, resulting in reduced surface plastic deformation and a decreased wear depth. In addition, during the curing process, epoxy located within pores and microcracks on the coating surface tends to undergo shrinkage, leading to the formation of voids. The presence of nano SiO₂ in the epoxy matrix suppresses curing shrinkage, promotes the filling of pores, and produces a denser epoxy structure. Consequently, the formation of wear-induced microcracks is inhibited, and interfacial delamination under repeated loading conditions is significantly reduced.

Among the sealed coatings, the sample containing 2 wt.% nanosilica (AM-E2S) exhibited the lowest wear depth and friction coefficient. The wear depth decreased progressively with increasing nanosilica content up to 2 wt.%, followed by a sharp increase at 3 wt.%. This behavior can be attributed to nanoparticle agglomeration at higher filler contents, which hinders uniform dispersion and weakens the bonding between the epoxy matrix and the coating surface. During sliding, poorly bonded agglomerates are more likely to detach, leading to increased wear.

The friction coefficient showed a similar trend, with the AM-E2S sample exhibiting the lowest value of approximately 0.21. The reduction in friction is associated with improved surface smoothness and enhanced load-bearing capacity resulting from effective pore filling and reinforcement by uniformly dispersed nanosilica.

Wear rate measurements further confirmed these findings. As shown in Table 4, the AM-E2S coating exhibited the lowest wear rate, indicating superior abrasion resistance. At the optimal nanosilica content, the epoxy matrix effectively penetrates the coating pores while nanosilica particles enhance hardness and reduce surface roughness, collectively improving tribological performance.

Table 4. Wear rates of coating samples

Sample	Wear rate (µm/s)
AM	0.411
AM-E	0.333

AM-E0,5S	0.294
AM-E1S	0.232
AM-E2S	0.151
AM-E3S	0.333

4. Conclusion

This study investigated the effect of nanosilica-modified epoxy sealing on the tribological performance of arc-sprayed AlMg alloy coatings. The results demonstrate that epoxy impregnation significantly improves wear resistance by reducing wear depth, friction coefficient, and wear rate. The incorporation of nanosilica further enhances these improvements, with an optimal nanosilica content of 2 wt.% providing the best overall performance. Excessive nanosilica content leads to particle agglomeration, which negatively affects wear resistance. The findings provide a practical guideline for optimizing epoxy-based sealing treatments to enhance the wear resistance of arc-sprayed AlMg coatings in demanding service environments.

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