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Influence of Surface Roughness Variation on the Quality and Adhesion of Hot-Dip Galvanized Coatings on Medium Carbon Steel

[1]*Suprihanto A, [2]Wibowo D B, [3]Umardani Y

[1,2,3]Mechanical Engineering Department, Diponegoro University, Semarang, Central Java, Indonesia

*Corresponding Author's E-mail: agusm90@yahoo.com

***Abstract* - This study investigates the influence of surface roughness on the coating thickness, microstructure, and mechanical properties of hot dip galvanized medium carbon steel. Despite its widespread industrial application, the HDG process in small and medium-scale industries remains poorly optimized, particularly in terms of surface preparation. The surface roughness of steel plays a critical role in determining the formation, diffusion, and bonding quality of the zinc coating layer. In this work, the influence of surface roughness on the quality of HDG coating was evaluated.**

The surface roughness was varied by mechanical polishing using sandpapers with grit numbers 100, 400, 800, and 2000. All specimens underwent standard pre-treatment, including degreasing, pickling in 32% HCl, and fluxing with zinc ammonium chloride before immersion in molten zinc at 450–455°C for 3 minutes. Experimental results showed that increasing surface roughness led to a significant rise in coating thickness and microhardness values. The highest coating thickness was observed on the specimen with the roughest surface (grit 100) reaching 246 µm, while the lowest value (73 µm) was recorded for grit 2000. The micro-Vickers hardness followed a similar trend, where higher surface roughness produces the formation of harder intermetallic phases, increasing hardness up to 67.47 HV. However, bending tests indicated that the coatings were relatively brittle due to the dominance of Fe–Zn intermetallic compounds.

Proper control of surface topography before galvanizing can improve coating adhesion, diffusion bonding, and mechanical performance, which are essential for enhancing corrosion protection and service life of galvanized components.

Keywords: hot dip galvanizing, medium carbon steel, surface roughness, coating thickness hardness.

I. INTRODUCTION

Steel remains one of the most essential structural materials used across industries due to its excellent mechanical strength, toughness, and cost-effectiveness. However, its major drawback lies in its susceptibility to corrosion when exposed to humid, marine, or industrial environments. Corrosion not only reduces the mechanical integrity of steel components but also leads to significant economic losses worldwide [1, 2, 3]. To mitigate this problem, various protective coatings have been developed, among which *hot dip galvanizing* (HDG) has become one of the most durable and cost-efficient surface protection techniques [4, 5, 6].

The HDG process involves immersing a cleaned steel substrate into molten zinc, forming a metallurgically bonded coating through mutual diffusion between iron (Fe) and zinc (Zn) atoms. This diffusion results in the formation of several Fe–Zn intermetallic layers that serve as a physical and electrochemical barrier against corrosion. The resulting coating is typically composed of multiple layers — η (eta, pure zinc), ζ (zeta, $FeZn_{13}$), δ (delta, $FeZn_7$), and γ (gamma, Fe_3Zn_{10}) — each contributing differently to the coating's mechanical and corrosion-resistant properties [7, 8].

The performance of HDG coatings is highly dependent on various process parameters, including zinc bath composition, immersion time, bath temperature, withdrawal speed, and — critically — the surface condition of the steel substrate prior to dipping [9, 10, 11]. Among these factors, surface roughness plays a particularly important role. The surface topography affects the nucleation and growth of Fe–Zn intermetallic layers, influencing coating uniformity, adhesion strength, and final mechanical behavior [12, 13]. A rougher surface provides more active sites for reaction, facilitating diffusion and anchoring of zinc, while smoother surfaces tend to yield thinner coatings with weaker adhesion.

Numerous studies have explored the general influence of process parameters on galvanizing quality, yet research focusing specifically on *the quantitative relationship between*

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surface roughness and coating mechanical performance for medium-carbon steel remains limited. Medium carbon steel is widely used in structural applications — such as bridge construction, tanks, and shipbuilding — where both strength and corrosion resistance are essential [14, 15, 16]. Its chemical composition (approximately 0.3–0.59% C) allows it to form stable intermetallic compounds with zinc under controlled galvanizing conditions. However, insufficient understanding of how its surface morphology affects diffusion kinetics has hindered process optimization in smaller manufacturing industries.

Prior works [17, 18, 19] have shown that the coating thickness in HDG increases with immersion time and bath temperature. Yet, these parameters cannot be optimized independently of surface texture, since roughness determines the interface contact area and the number of active nucleation sites for zinc crystallization. The role of surface roughness becomes even more significant medium carbon steel, where oxide formation and uneven wetting can strongly affect coating growth [20, 21].

Moreover, surface roughness directly influences not only coating adhesion but also the microstructural evolution of the Fe–Zn system. According to diffusion theory, atomic migration during galvanizing follows a vacancy diffusion mechanism, in which zinc atoms substitute iron atoms at the interface, forming a graded intermetallic zone. The diffusion rate is proportional to the surface energy and contact area between zinc and the substrate — both of which are controlled by the initial roughness profile (Ra, Rz, and Rv values). Thus, it can be hypothesized that higher surface roughness accelerates diffusion, resulting in thicker coatings and higher hardness due to the formation of denser intermetallic compounds.

In addition to corrosion protection, the mechanical behavior of the galvanized coating, including hardness and bending resistance, also determines its functional reliability. Excessively hard coatings may exhibit brittleness, while overly thin coatings may lack durability. Therefore, achieving an optimal balance between coating thickness and mechanical properties is critical. Understanding the influence of surface roughness can guide manufacturers in adjusting pre-treatment and polishing methods to achieve desirable coating performance. In this study, a systematic investigation is conducted to analyze the effect of surface roughness on the coating characteristics of medium carbon steel subjected to hot dip galvanizing. Through this analysis, the work seeks to contribute a deeper understanding of surface engineering effects in HDG processes, providing practical insights for optimizing coating performance in small and medium-scale industries that utilize medium carbon steel for structural applications.

II. METHODS

The base material used in this research was medium carbon steel, a medium-strength structural steel commonly used for mechanical and construction applications due to its favorable balance between ductility, weldability, and strength. The chemical composition of the medium carbon steel used in this study was approximately: 0.59% C, 0.35% Si, 0.81% Mn, 0.015% S, 0.012% P, and the balance Fe.

Rectangular specimens with dimensions of 50 mm × 50 mm × 3 mm were prepared by cutting from commercial steel plates. The specimens were first cleaned using acetone to remove oil, grease, and contaminants. The coating material was high-purity zinc (99.995%), obtained from industrial-grade Nyrstar zinc ingots. The zinc was melted in a graphite crucible within an electric furnace equipped with a temperature controller capable of maintaining the bath within ±5°C of the target temperature.

To produce different surface roughness levels, the steel specimens were mechanically abraded using emery sandpapers of grit numbers 100, 400, 800, and 2000, which correspond to different surface textures and mean roughness values (*Ra*).Surface roughness is controlled through varying sandpaper grits 100, 400, 800, and 2000representing different levels of surface finish. The resulting coatings are evaluated in terms of thickness, microstructure, micro-Vickers hardness, and bending behavior. The surface roughness was measured using a Mitutoyo Surftest SJ-210 surface profilometer. The measurements were conducted at five random points on each specimen to ensure consistency, and the arithmetic mean values (Ra), average maximum height (Rz), and maximum valley depth (Rv) were recorded.

Proper surface pre-treatment is essential in HDG to ensure clean metal surfaces and good metallurgical bonding between the steel substrate and the zinc coating. The specimens underwent a three-step pre-treatment sequence:

1. Degreasing: The samples were immersed in a sodium silicate (*water glass*) solution at 70°C for 5 minutes to remove oil and organic residues.

2. Pickling: This step aimed to dissolve surface oxides and mill scales using a 32% hydrochloric acid (HCl) solution for 5 minutes at room temperature.
3. Fluxing: After pickling, the specimens were immersed in a zinc ammonium chloride ($ZnCl_2 + NH_4Cl$) flux solution maintained at 90°C for 3 minutes. This step promotes

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surface activation and prevents oxidation before immersion in molten zinc.

Following fluxing, all specimens were dried in warm air (~80°C) to ensure complete removal of moisture, which is critical to avoid splattering or oxidation during immersion in molten zinc. The galvanizing process was performed using a custom-built HDG furnace capable of operating at a temperature range of 400–500°C. Zinc ingots were melted in the crucible and stabilized at 450–455°C before immersion. Each specimen was dipped into the molten zinc for 3 minutes using stainless-steel tongs, ensuring full submersion. The immersion time was chosen based on standard practice for medium-carbon steels to allow sufficient Fe–Zn diffusion without excessive intermetallic growth. After the immersion, each specimen was withdrawn slowly at a uniform rate of approximately 20 mm/s to minimize coating irregularities. The galvanized samples were cooled in still air to room temperature before further testing.

After galvanizing, each specimen underwent several tests to characterize the resulting coating's morphology, mechanical properties, and microstructure. The coating thickness was measured using an optical microscope (Olympus BX53) equipped with a digital micrometer stage. Each specimen was cross-sectioned, mounted in epoxy resin, ground, polished, and etched using 2% Nital solution to reveal the coating boundaries. The coating thickness was determined as the average of five measurements taken at different points along the cross-section.

The micro-Vickers hardness test (HV) was conducted using a Shimadzu HMV-G microhardness tester. Indentations were made on the surface of the galvanized coating under a 100 g load and a dwell time of 15 seconds. For each sample, five measurements were taken, and the average value was calculated. The bending behavior of the coated specimens was evaluated according to the ASTM E290-14 standard for guided bend testing. The specimens were bent at a constant rate until fracture or until the bending angle reached 45°. This test was designed to assess the coating's adhesion and ductility.

The microstructure of the galvanized coatings was observed under an optical microscope after etching with 2% Nital to reveal the Fe–Zn intermetallic layers. The formation and thickness of the η, ζ, δ, and γ layers were analyzed and compared among the surface roughness variations.

All experimental results were tabulated and analyzed using descriptive statistical methods. The relationships between surface roughness (Ra) and coating thickness, as well as between Ra and hardness, were presented graphically.

These values indicate a significant variation in surface texture, which is expected to influence the wetting and diffusion behavior during hot dip galvanizing.

The correlation between roughness and coating behavior will be discussed in Section 4, where the microstructural evolution and mechanical implications are analyzed in detail.

III. RESULTS AND DISCUSSION

The effect of grit on the surface roughness as shown in Table 1. As expected, the coarser grit (100) generated deep grooves and valleys with high roughness parameters (Ra = 2.373 µm, Rz = 15.524 µm, Rv = 7.677 µm), while the finest grit (2000) produced a nearly mirror-like finish (Ra = 1.101 µm).The surface morphology of the medium carbon specimens exhibited significant variation after mechanical polishing using different sandpaper grits.

Table 1: The average of surface roughness before galvanizing

Grit No	Ra	Rz	Rv
100	2.373	15.524	7.677
400	1.851	12.265	6.391
800	1.561	11.864	5.963
2000	1.101	11.218	5.865

The effect of grit on the coating thickness and hardness as shown in Table 2. The coating thickness decreased progressively with smoother surfaces, from 246 µm for the roughest surface (grit 100) to only 73 µm for the smoothest one (grit 2000). The higher surface roughness enhances zinc layer growth due to accelerated interdiffusion between Fe and Zn atoms. During the hot dip galvanizing process, molten zinc penetrates the micro-valleys of the steel surface, forming a strong metallurgical bond. For rougher surfaces, the increased surface area and localized diffusion fronts promote a thicker intermetallic layer. Conversely, smoother surfaces exhibit limited diffusion and poorer wetting, resulting in thinner and sometimes discontinuous coatings.

These surface conditions greatly affect how molten zinc wets and react with the steel surface during immersion. Rougher surfaces have higher surface energy and provide more nucleation sites for zinc adhesion. Moreover, the micro-asperities increase the effective contact area, thereby facilitating faster Fe–Zn diffusion at localized high-temperature points. In contrast, smooth surfaces limit diffusion due to fewer nucleation sites and slower wetting kinetics. The observed differences in Ra, Rz, and Rv suggest that topographical variation is not only in amplitude but also in the overall surface geometry, which strongly influences coating formation.

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Table 2: Coating thickness And Hardness

Grit No	Thickness (µm)	Hardness (VHN)
100	2.373	15.524
400	1.851	12.265
800	1.561	11.864
2000	1.101	11.218

Another factor contributing to the increased coating thickness on rougher surfaces is the micro-trapping effect of molten zinc within surface asperities. These small cavities serve as reservoirs for zinc, leading to prolonged local reaction times even after partial withdrawal from the molten bath. These indicate that controlling surface roughness can effectively tailor coating thickness without altering major process parameters such as temperature or immersion time. The results are particularly beneficial for small-scale galvanizing industries that seek to improve coating quality through simple surface preparation adjustments.

As shown in Table 2, the hardness values show a strong correlation with coating thickness. The thickest coating (246 µm) at grit 100 exhibited the highest hardness (67.47 HV), while the thinnest coating (73 µm) at grit 2000 had the lowest hardness (42.97 HV). This behavior is associated with the presence and distribution of Fe–Zn intermetallic compounds within the coating structure. The hardness variation is produced by the intermetallic phases γ, δ, and ζ. These phases possess significantly higher hardness compared to the outer η layer (pure zinc). This is because their ordered crystal structures and high Fe content. Therefore, thicker coatings, which generally contain more of these intermetallic phases, tend to exhibit higher overall hardness. Figure 1 show the typical microstructure at surface of the specimens.

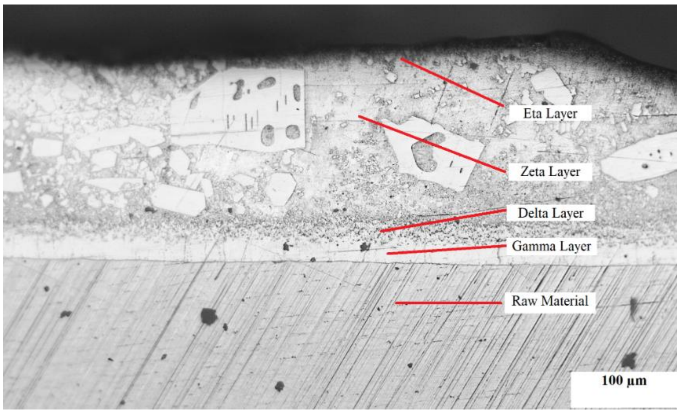

Figure 1: The microstructure at the surface

The correlation between roughness and hardness suggests that increased surface roughness accelerates Fe–Zn diffusion and enhances intermetallic formation. This results in a denser and harder coating. However, excessive growth of intermetallic layers may cause embrittlement, as observed in the bending test results.

To determine the bond strength, a bending test was conducted. The results of the bending test are shown in Table 3.The bending test provides insight into the ductility and adhesion of the coating. All galvanized specimens, regardless of roughness, exhibited brittle fracture of coating at approximately 120° of bending. This indicates that the coatings were relatively hard and less ductile. These is a characteristic typical of intermetallic Fe–Zn compounds.

Table 3: Results of bending test

Grit	Specimen No (Ra, µm)	150°	120°	90°	60°	45°
100	1 (2.373)		✓	✓	✓	✓
	2 (1.937)		✓	✓	✓	✓
	3 (1.911)	✓	✓	✓	✓	✓
400	1 (1.118)		✓	✓	✓	✓
	2 (0.963)	✓	✓	✓	✓	✓
	3 (1.159)	✓	✓	✓	✓	✓
800	1 (0.661)	✓	✓	✓	✓	✓
	2 (0.581)	✓	✓	✓	✓	✓
	3 (0.488)		✓	✓	✓	✓
2000	1 (0.416)	✓	✓	✓	✓	✓
	2 (0.515)		✓	✓	✓	✓
	3 (0.395)	✓	✓	✓	✓	✓

The brittle behavior arises from the crystal structure of Fe–Zn intermetallic, which are primarily ordered and covalently bonded. The δ and ζ phases, in particular, are known for their high hardness but poor plasticity. When subjected to bending stress, microcracks initiate at the Fe–Zn interface due to mismatched elastic moduli between the steel substrate and the coating. These cracks propagate rapidly through the intermetallic layers, leading to coating delamination or fracture.

Interestingly, specimens with rougher surfaces (grit 100 and 400) showed slightly better coating adhesion compared to smoother ones. This improvement can be attributed to the mechanical interlocking effect provided by surface asperities, which anchor the coating more effectively. However, despite this improvement, the overall ductility remained limited because the intermetallic layer thickness was substantial.

These observations imply that while increased surface roughness enhances coating adhesion and thickness, it may also lead to a more brittle coating. Therefore, optimization of surface roughness is necessary to achieve a balance between coating hardness and flexibility.

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IV. CONCLUSION

This research investigated the effect of surface roughness on coating thickness, microstructure, and mechanical properties of hot dip galvanized (HDG) medium carbon steel. The results clearly demonstrate that surface roughness plays a dominant role in determining the diffusion behavior and resulting mechanical characteristics of galvanized coatings. Rougher surfaces promoted the formation and growth of δ and ζ intermetallic layers, while smoother surfaces favored a thinner, uniform η layer. Although rougher surfaces improved adhesion due to mechanical interlocking, they also increased brittleness as a result of higher intermetallic content. Furthermore, for achieving the desired balance between coating thickness, hardness, and ductility. Controlling the surface roughness before galvanizing offers a simple yet powerful means of tailoring coating performance without altering immersion time or bath temperature.

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