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Investigation of Mechanical and Electrical Properties of Hot-Dip Galvanized ASTM A106 Gr B Steel

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ABSTRACT

The primary objective of this study is to validate the mechanical properties of ASTM A106Gr B carbon steel through a simulation process. This involves examining the stress values of the steel samples before and after undergoing the hot dip galvanizing (HDG) process, the commercial software Solidworks 2018 for a finite element analysis (FEA) was employed. Additionally, the study also investigates the electrical properties, low impedance ohmmeter was used to measure resistivity, of the samples that have been immersed in a hot zinc bath for varying durations of 3, 5, and 8 minutes. It has been found the results of a numerical analysis demonstrated a satisfactory agreement between the galvanized and non-galvanized samples. The stress values were found closely aligned, with an error rate of 1% in relation to the experimental results. Regarding the electrical aspect, the practical tests revealed that an increase in the thickness of the zinc material on galvanized samples led to a decrease in resistivity. Conversely, the electrical conductivity exhibited an upward trend with increasing immersion time and zinc material thickness.

1. Introduction

Corrosion is a natural process that causes metal deterioration through electrochemical interactions with the environment [1]. The durability of the material can decrease, which leads to a decrease in the quality of the metal due to the high-water vapor content in the air [2].

The corrosion issues in pipelines for transportation within the petroleum sector have resulted in significant damage and subsequent maintenance costs and time consumption, and many scientists have conducted different types of research on the dangers of corrosion and its effects on the industrial world [3]. Several coating techniques are often applied to lower the cost of repair, extend the life of parts, and shield the base substance from outside effects [4]. They achieve their main function when the coatings are solid, impermeable, evenly distributed over the surface, and have good adhesion and resistance to heat and corrosion [5]. The ASTM A106Gr B steel plays an important role in the petroleum sector due to its superior strength and formability [6].

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Hot-dip galvanizing is a protective coating technology frequently used to prevent corrosion damage in steel structures [7]. This process holds great importance in ensuring the longevity of steel structures. Unlike other coating methods such as epoxy, galvanization is considered to be environmentally friendly. The coating applied during the galvanization process is known to have a remarkable lifespan, lasting for over 50 years.

For over half a century, the hot-dip galvanized HDG steel has been utilized as a coating pipes, providing a clean, economical, and efficient approach to protection steel from corrosion. The process of hot-dip galvanizing HDG involves applying zinc coatings, through the steel being immersed in a molten bath, which results in the deposition1 of thin layers of zinc on it [8]. making it a reliable method for protecting steel. Pretreatment, steel properties, galvanizing bath properties, process parameters, manufacturing process, and service condition are among the processes that are important to know in order to know the quality of the coating and the correctness of the galvanizing process [9]. In this research, electrochemical impedance spectroscopy (EIS) was performed to evaluate and determine the barrier properties of the coat [10]. Evaluating the structural features of pipelines using simulation is essential and holds considerable importance in avoiding failures [11]. therefore, it is vital to undertake preventive measures (the mechanical and electrical) properties to mitigate such problems. The dipping time in the zinc bath plays a major role in the coating layer thickness [12,13]. Literature has extensively examined the mechanical properties of steel following the application of HDG coating, shedding light on various aspects of the process.

In an investigation done by A Hakim *et al.*, [13] studded the impact of immersion time in hot dip galvanizing (HDG) on the Rockwell hardness (HRb) and microstructure of Low-carbon steel was investigated. The study involved immersing the steel specimens for 3, 6, 9, and 12 minutes in the HDG process. The resulting microstructure was examined using scanning electron microscopy (SEM), focusing on the zeta, delta, and gamma phases. Additionally, the presence of elements such as Fe, Zn, Mn, Si, and S in the coated specimens was analyzed. It was observed that the maximum hardness of 76.012HRb was achieved after a 3-minute immersion in the zinc bath [14].

In their study, Elżbieta *et al.*, [15] focused on optimizing the heat treatment of coatings and its impact on the mechanical and functional properties of steel and cast iron. They also examined microhardness and conducted microscopic observations using EDS. The researchers found that while the applied heat treatment resulted in an increase in coating hardness, excessively high temperatures could lead to cracking and delamination of the coating. Additionally, they observed that as the processing temperature increased, the structure of the coating changed, with an increase in the iron content in individual zinc phases. Furthermore, when zinc coating was deposited on cast iron, it exhibited greater inhomogeneity.

In a separate study conducted by Adnan Calik *et al.*, [16] three different galvanizing processes were employed to investigate the microstructure, tensile behavior, and hardness of AISI 4140 steel sheets. The researchers were measured three layers of coating, for three different types of coating zinc. Study was observed there are no effective in improving in the tensile strength of the galvanized AISI 4140 steel samples compared to the uncoated with zinc ones.

In the investigation conducted by Musbah Kharis Maatgi, [17] the focus was on analyzing the low carbon steel manufactured by a Libyan company. The study encompassed both the rolling process (hot and cold) and the hot dip galvanizing process. The objective was to examine the impact of these processes on the mechanical properties and microstructure of the steel. The findings revealed that cold rolling resulted in an increase in the yield strength when compared to hot rolling with hot dip galvanizing (HDG). On the other hand, there was a decrease observed in the yield stress, tensile strength, and hardness of the steel subjected to the HDG process. However, an interesting observation was made regarding the extension rate of the steel produced through hot-dip galvanizing. It was found that this process led to an increase in the extension rate, contributing to the growth of granules. This, in turn, enhanced the steel's ability to undergo subsequent manufacturing processes by facilitating its formability.

In the background of the review conducted by German Pachurin *et al*., [18] the focus of the investigation revolves around the preferred technique for coating steel from severe environmental conditions for parts under a high-load operation, which is galvanization. Simultaneously, despite their impact on the durability of delicate specimens, the endurance threshold of samples with stress concentration rises. Various forms of saturation distribution enhance the corrosion resistance of steels; however, there is a lack of information regarding the ideal values for coating thickness that have been thoroughly examined. The determination of theoretical and experimental data makes it challenging to anticipate the physical and mechanical aspects of coated metals and alloys.

Within the inquiry conducted by Ali Rafie, [19] was studied the effect of hot dip galvanizing on the steel of B500B. A numerical analysis was performed using the SolidWorks numerical analysis program, to determine the mechanical properties before and after coating. The results were in line with analytical results. Additionally, experimental tests were conducted to assist the influence of immersion time on the zinc layer, conductivity and resistivity. It was deduced that stresses escalate with an increase in the coating layer’s thickness, furthermore the study concluded that the conductivity of the coated steel increases while the resistivity decreases with an increase in thickness of the coating layer.

Previous studies have primarily examined the effects of galvanization on the mechanical properties of materials. However, there is a lack of research investigating the electrical properties, such as resistivity and conductivity, specifically in relation to hot-dipped zinc-coated pipes. The current investigation aims to fill this gap by focusing on the mechanical-numerical simulation, electrical characteristics, and the influence of microstructure on the coating of ASTM A 106 Gr B with HDG. These aspects are crucial for understanding both the mechanical and electrical properties of the coated pipes. It is important to note that few prior research has been conducted on this specific subject, utilizing this particular type of analysis. Therefore, this original approach holds significant importance for the petroleum sector in Iraq.

2. Methodology

The study utilized petroleum-based materials, specifically the ASTM A106 Gr B carbon steel pipe with an outer diameter of 273mm. Table 1 presents the composition of the carbon steel ASTM A106 Gr B in comparison to the standard. The examination and measurement of the steel were conducted at a state company to ensure compliance with the set standards.

The steel samples underwent a coating process known as Hot-Dip Galvanizing (HDG). This method involves immersing the samples in a bath of molten zinc to create a layer and adherent zinc or zinc alloy coating of the steel surfaces. The HDG process follows the guidelines set by ASTM A123 and comprises three main steps: surface preparation, galvanizing, and inspection. The temperature of the zinc bath reached 447 ˚C, and its chemical composition is detailed in Table 2. The dipping time for the samples were 3, 5 and 8 minutes, and all samples were prepared prior to the dipping process.

Table 1
Displays the chemical composition of ASTM A106 Grade B in weight percent

Elements wt.%	C	Mn	P	S	Si	Cr	Cu	Ni
Standard the ASM	≤0.3	0.29-1.06	≤0.035	≤0.035	0.01	≤0.04	≤0.04	
Experimental T2	0.088	0.91	0.0183	0.004	0.202	0.0211	0.0161	0.011

Table 2
The zinc bath chemical composition (wt.%)

Zn	Al	Pb	Cd	Mg
99.979	0.031	0.0	0.0	0.0

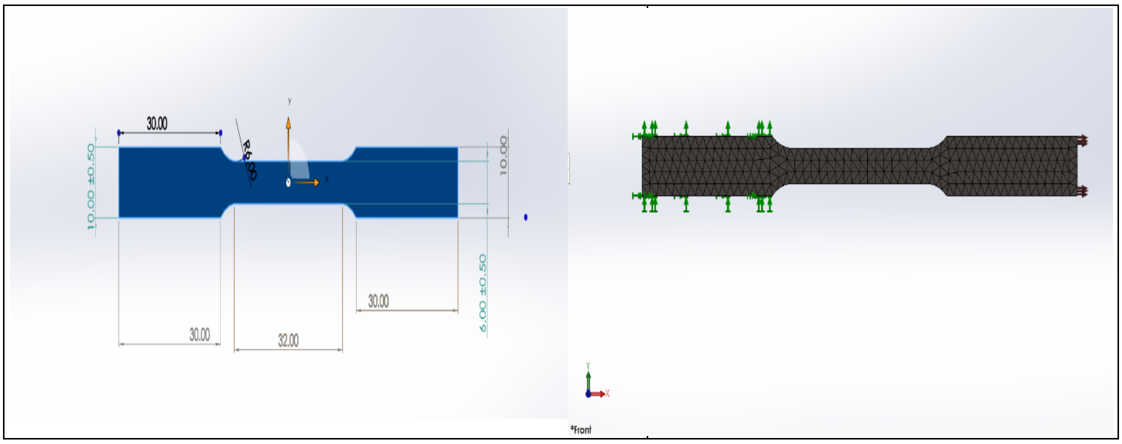
3. Numerical analysis

Two simulations were conducted for numerical modeling using the commercial FEA software Solidworks 2018 [20]. The initial tensile sample was analyzed without any coating, while the subsequent sample was coated with hot dip galvanized HDG in order to investigate its mechanical properties.

The input geometries were appropriately meshed [21] to ensure that the minimum element length is smaller than the minimum geometric formation. The draw with dimensions and the meshed geometries are illustrated in Figure 1a and Figure 1b.

The simulation utilized the tensile strength for both uncoated and coated steel. In each analysis, the meshed bodies were anchored at one end and subjected to a tensile stress of 511 MPa at the opposite side.

The specimens were discretized using around 6724 tetrahedral solid elements. The mesh exhibited uniformity across the gage length, as shown in Figure 1, without any localized mesh densification (total: 6724 tetrahedral solid elements). The geometric layout is illustrated in the corresponding figure1. Resulting in consistent final stress outcomes.



(a) (b)

Fig. 1. Analytical simulation a) geometric configuration tensile test b) meshed a tensile sample.

4. Results and Discussion

4.1 Numerical Results

The simulation outcomes for the strength (UTS and yield) stresses, as well as the experimental findings detailed in Table 4 for both uncoated and HDG-coated samples, demonstrate a concurrence between the simulation and experimental data. Additionally, Figure 10 illustrates the simulation results for both uncoated and coated samples, with the fracture area being highlighted as well. The results from the tensile test conducted on uncoated steel were consistent with findings of the study [22], with the ultimate tensile (UTS) and yield values being (514 MPa) and (392MPa) respectively. The stress from the experimental values were found closely aligned to the simulation results with an error rate of 1%.

Table 3
The strength of the ASTM A106 carbon steel without and with HDG

	Ultimate stress (MPa)	Yield stress (MPa)
Experimental Result Without coating	511	465.26
Simulation Result Without coating	513	325
Experimental Result With coating (HDG)	501	452
Simulation Result With coating (HDG)	496	375

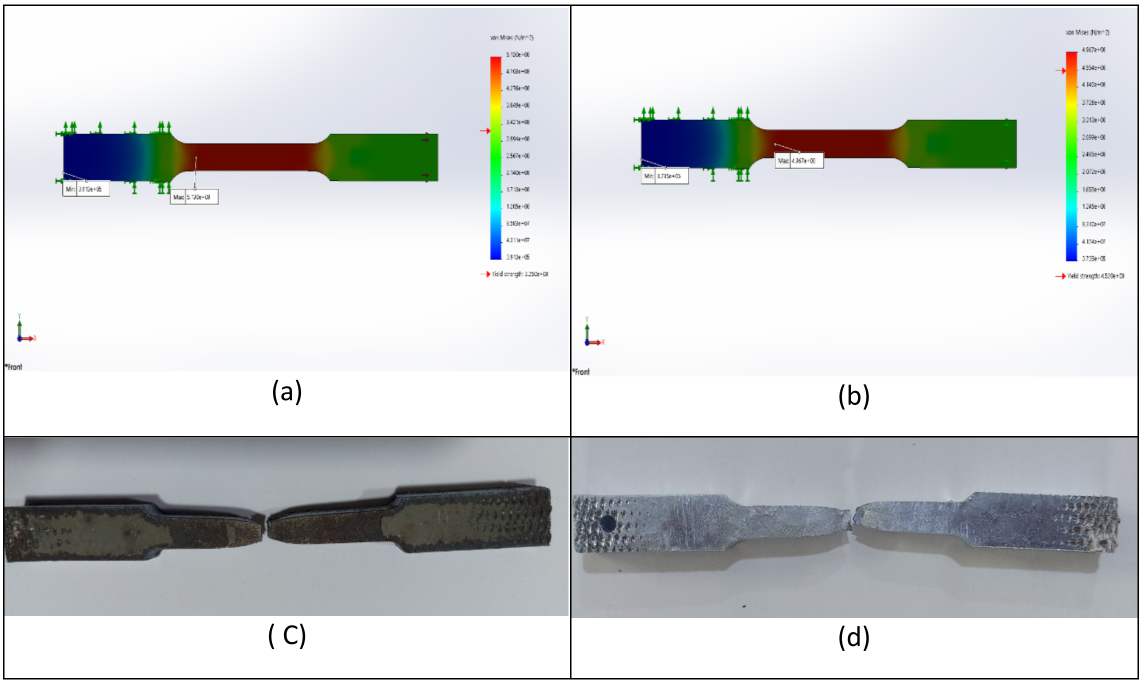

(a) (b)
(C) (d)

Fig. 2. The stress distribution for ASTM A106 Gr B a) uncoated tensile stresses and b) coated tensile stress steel c) fracture area uncoated steel d) fracture area coated steel

4.2 The Electrical Results

Conductor's resistance is expressed using the formula (1) has been used in this study:

$$R = \frac{\rho L}{A} \tag{1}$$

Where, ρ = Resistivity of the conductor (Ω·m), L = length of the conductor (m), A = Area of the cross-section of the conductor (mm^2). So, the conductivity value given by the equation and equal invers of the Resistivity

$$\sigma = \frac{1}{\rho} \tag{2}$$

The impact of zinc coating thickness on the electrical properties of A106 Gr B and galvanized steel, the coating thickness was varied for several specimens. Table 4 summarizes these results and compares them to the electrical properties of steel without (HDG).

Table 4
Electrical properties for steel ASTM A 106 Gr B without and with (HDG).

Time dipping	Zinc thickness(µm)	resistivity(µΏ.mm)	conductivity (µS/mm)
0	0	113.002	0.00885
3 min	135	109.34	0.009146
5 min	145	107.36	0.009314
8 min	204	106.59	0.009382

The relationship between the dipping time and the coating thickness was experimentally examined, as shown in Figure 3. This figure indicates that increasing dipping time leads to an increase in the coating thickness, as expected. This allows for controlling coating thickness by adjusting dipping time, which aids in determining the optimal dipping time to achieve the desired thickness, this particular case was examined in two studies [12,13]. Figure (4) show the variation of direct current resistance (µΩ) with the zinc thickness (µm). As the zinc thickness increases, the electrical resistance slightly increases. This helps in understanding the influence of zinc thickness on the conduction of electric current. The D.C resistance of these samples was then measured using a low-resistance ohmmeter. The experimental results obtained were utilized to estimate conductivity and resistivity using eq. (1) and Eq. (2). Figures 5 and 6 demonstrate the electrical conductivity and resistivity, respectively, as a function of varying zinc thickness. The Figure (5) presents the results of comparing the electrical conductivity with zinc thickness (204 μm) to those of other thicknesses (135and 145 μm). This is because there are more conductive paths between zinc and steel, and the zinc coating fills in the voids left by the steel's particles overlapping with the zinc. The physical specification of the materials [23] states that zinc has a conductivity that is higher than steel's. This suggests that an increase in zinc thickness causes a corresponding rise in conductivity. Because zinc has the lowest resistivity compared to steel, Figure (6) illustrates how resistivity decreases from 109.34 (Ω·cm) to 106.59 (Ω·cm) when zinc thickness increases from (135 to 204) µm. This result is predicted by the inverse relationship between conductivity and resistivity, which is represented by eq. (1) and is based on the findings in Figure (7).

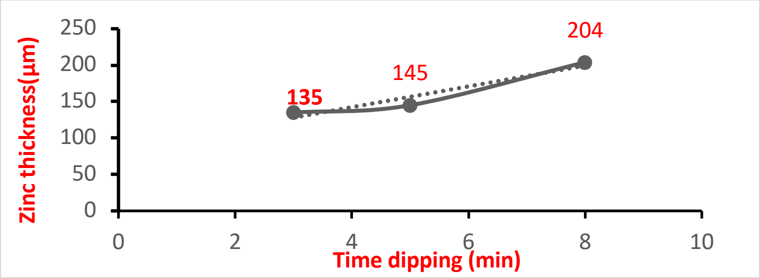


Fig. 1. The Time dipping the layer thickness of the zinc

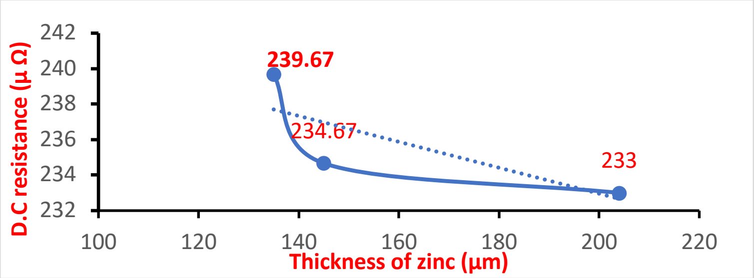


Fig. 2. D.C Resistance vs the layer thickness of the zinc

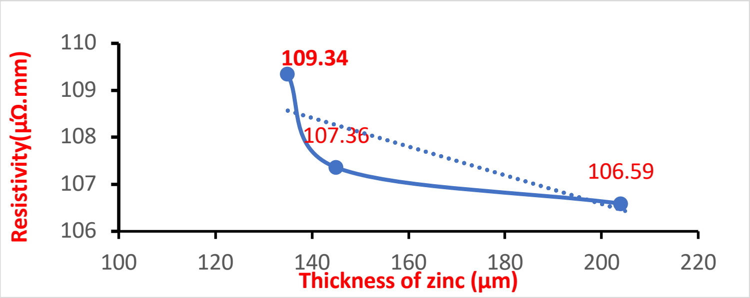


Fig. 3. Conductivity VS the galvanize thickness layer

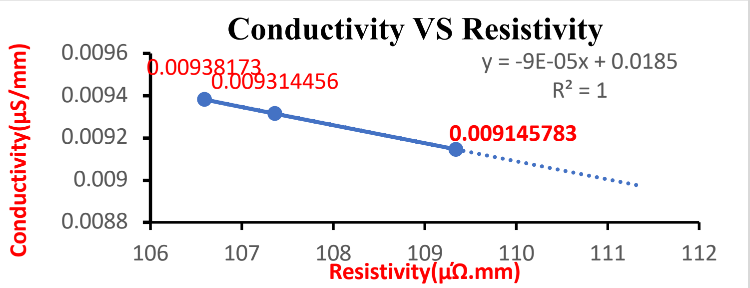


Fig. 4. Resistivity with the layer thickness of the zinc

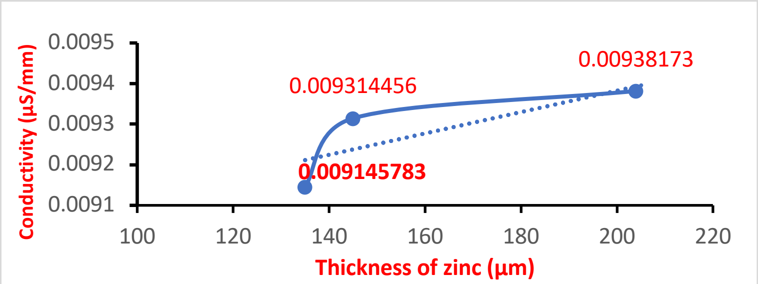


Fig. 5. The conductivity vs the resistivity

4. Conclusions

The present study on the mechanical and electrical properties of the ASTM A106 Gr B before and after coated with (HDG) yield the following findings:

1. The numerical modelling results showed that the coated surface with HDG decreases the stresses like the experimental result.
2. The stress from the experimental values were found closely aligned to the simulation results with an error rate of 1%.
3. Analysis of the numerical solution revealed that the highest principal stress in uncoated and coated steel scenarios are within the identical to the gauge length. The peak stress is around 513 MPa for the uncoated steel and 496 MPa for the coated steel, demonstrating a mere 4% deviation from the experimental findings.
4. With the rise in zinc thickness, there was a decrease in resistivity, while conductivity increased as the D.C resistance reached its minimum level.

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