Influence of hot-dip coatings on mechanical and corrosion behaviors of steel bolts

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Abstract

Steel bolts are used for fastening structural components together, and hence high durability in terms of the mechanical and corrosion resistance is inevitably critical. The present study systematically compares the performance of carbon steel (CS), stainless steel (SS), steels with Fe-Zn and with Zn-Ni protective coating layers prepared with hot-dip procedures (GI and GN), for the fastener applications. The torsion and hardness tests, together with the salt spray study, show that CS has poor corrosion resistance, whereas SS exhibits relatively low yield strength. On the other hand, GI and GN show promising corrosion protection, without compromising the mechanical integrity. Furthermore, the microstructure of the samples is examined to analyze the rigidity of the coatings and to explain the corresponding behaviors of the materials.

Keywords : Bolts, Corrosion, Hot dip galvanizing, Torque, Twist angle
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Introduction

Bolting is a joining process which is employed commonly in the construction applications. Its advantages include a good performance under fluctuating stress, no induced internal stress, and simplicity of installation and inspection.(1,2) High durability in terms of the mechanical and corrosion resistance is inevitably critical for fasteners, and hence materials design and selection of bolts and nuts are important. Carbon steel shows adequate mechanical strength, yet it is highly susceptible to corrosion. Red rust can easily form on carbon's steel bare surface with no protection.(3) On the other hand, stainless steel is praised for its remarkable corrosion resistance, yet its relatively low yield stress may exhibit a drawback.(4) Particularly, torques that are applied to stainless steel bolts in service could unintentionally exceed the yield points. Subsequently, the bolts lose its integrity, and removal and re-installment of fasteners during a following maintenance session become impossible.

Hot-dip coating which provides Fe-Zn or Zn-Ni intermetallic compounds in the coating interface could mitigate the shortcomings of carbon steel and stainless steel by providing improved corrosion protection, possibly without compromising the mechanical integrity. The process of immersing steel articles to molten zinc bath, namely hot-dip galvanization, render Fe-Zn intermetallic phases and Zn coating layers on the steels's surfaces. The coatings provide barrier and cathodic protection to steel.(5) Similarly, steels with Zn-Ni intermetallic phases and Zn coating layers on the steels' surfaces could be obtained if Ni pre-coating is provided prior to hot-dipping in a zinc bath. Enhanced corrosion protection has been observed for this latter case.(6,7,8,9)

A study was performed in this work to systematically compare the performance of carbon steel, stainless steel, carbon steels with Fe-Zn and with Zn-Ni protective layers prepared with hot-dip procedures, for the fastener applications. Under the same testing environments, torsion and hardness tests were conducted to assess the mechanical properties of the specimens, and the salt spray test was applied to characterize their susceptibility to red rust formation. The microstructure of the tested specimens was carefully characterized afterwards.

Materials and Experimental Procedures

4 groups of bolt specimens with distinct types of materials were used in this study: carbon steel, stainless steel, hot-dipped carbon steels with Fe-Zn and with Zn-Ni intermetallic coating layers. They will be termed herein CS, SS, GI, and GN, respectively. The first two were obtained commercially – the carbon steel ones were a high strength steel (grade 8.8, designating 800 N/mm^2 nominal ultimate tensile strength, and 640 N/mm^2 nominal yield strength),

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whereas the stainless steel was of 304 grade. The hot-dip specimens were prepared from carbon steel with the same grade as CS. The specimens with the dimension of L=38 mm and O.D.=20 mm were subsequently applied for the hardness measurement and corrosion tests. As for the torsion tests, the bolt specimens with L=115mm, O.D.=6 mm, and groves being removed were utilized.

Prior to hot-dipping for the preparation of the GI and GN specimens, carbon steel bolts were degreased in NaOH 10 wt.% at 60°C for 10 minutes, and pickled in 14wt.% for another 10 minutes. One set of the specimens were then applied with flux and directly submerged in a 450°C molten zinc bath for 1 minute, resulting in specimens with Fe-Zn intermetallic layers. For another set of specimens, electrodeposition of nickel from the Watts' bath was performed prior to fluxing and hot-dipping in the molten zinc bath, resulting in a formation of Zn-Ni intermetallic layers in the specimens.

The mechanical property analyses include hardness measurement and torsion tests. The bolts were cut lengthwise to measure cross-section hardness by Vicker hardness tester (Mitutoyo hardness testing machine) with 300 g test load and 15 s indentation time. The hardness data was collected across the width of the bolts from surface to core. ASTM E8M was followed to assess the behavior of the bolt materials under torsion as applied by a torsion testing machine (Instron Model torsion 55MT2-E3) with 180°/min controlled rotation rate (Figure1).

Salt spray test was performed, following ASTM B117, to evaluate the corrosion resistance of the four set of materials. The salt spray fog of 5 wt% NaCl solution was maintained for 432 hrs. The appearance of the bolt samples were recorded daily, and the Image-J software was used to determine the percentage area of red rust developed on the samples' surfaces.

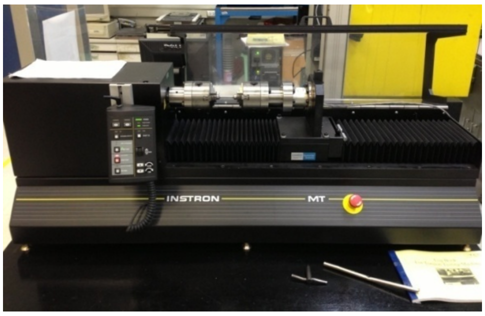


Figure 1. Torsion test specimen and torsion test machine (Instron model torsion 55MT2-E3)

Results and Discussion

The four groups of specimens were prepared successfully. Figure 2 shows an example of the cross-section of the bolts from GN group that was prepared for the hardness measurement. The hardness data of the bolt specimens, as reported in Figure 3, illustrates that the bolts from the CS, GI and GN group all exhibit comparable hardness of about 300 VHN near the surfaces. These values merely slightly decline along the width of the bolts. This indicates that the thermal load from the process of hot-dipping does not significantly affect the hardness of the materials. On the other hand, the hardness of the SS at the interface of about 330 VHN is relatively higher than other groups. Furthermore, the hardness appears to decrease along the width of the bolt as much as 30%. This could be owing to the forming process of the SS bolts that exhibit declining deformation rate from surface to core.[10] The intrinsic thin oxide films of SS should also contribute to the relatively high hardness near its surface.

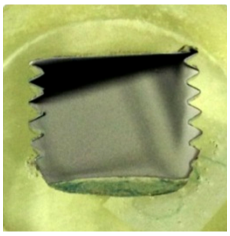


Figure 2. Cross section of a bolt from GN group as prepared for hardness measurement

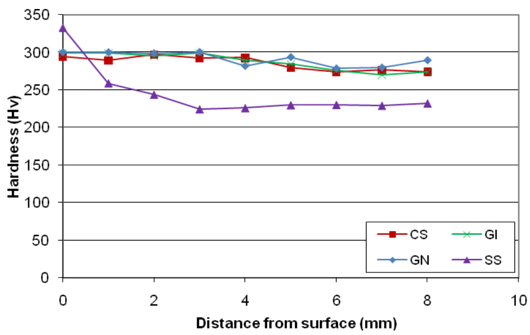


Figure 3. Hardness of the 4 groups of bolt specimens (CS, SS, GI and GN) along their thickness

The result from torsion tests are presented in Figure 4. Generally, all groups of the specimens exhibit plastic deformation. Furthermore, all of them appear to yield at similar levels of applied torque (T_y). In fact, the shape of the torque-twist angle curves of CS, GI, GN specimens and their ultimate twist angles (θ_u) and corresponding ultimate torques (T_u) appear somewhat similar to one another, indicating very small contribution, if any, of the hot dip coatings. The torsion test results do indeed parallel to the hardness measurements, in agreement with prior works.[11] The SS specimens, on the other hand, show higher θ_u. Moreover, the curve appears to exhibits relatively low strain hardening exponent. In fact, for the low twist angles of 0°-80°, as illustrated in Figure 4b, the SS bolt almost exhibits elastic perfectly plastic behavior, requiring practically no applied load for extensive plastic deformation. The results thus suggest lower integrity of SS bolts under torsion as compared to CS, GI, or GN counterparts. The parameter extracted from the torsion tests are summarized in Table 1. The appearance of the test specimens and their fracture surfaces are shown in Figure 5.

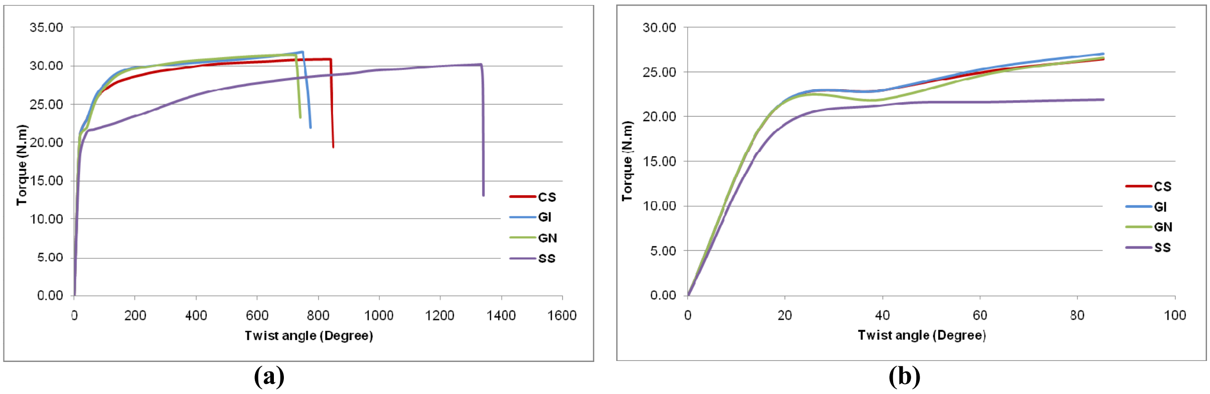


Figure 4. Comparison of torque versus twist angle of the 4 groups of specimens (CS, SS, GI and GN) throughout the test sessions (a) and at low twist angles (b).

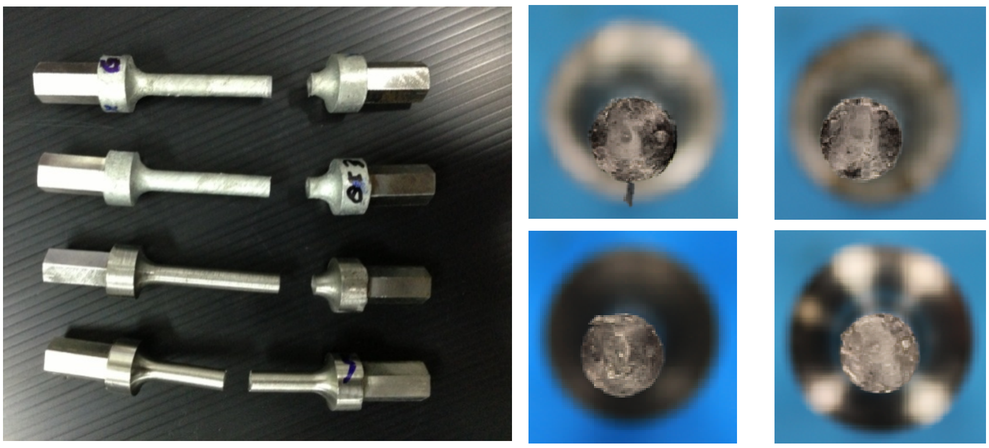


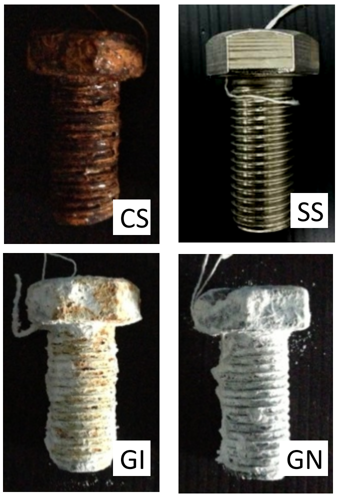
Figure 5. Side views and fracture-surface views of the 4 groups of specimens (CS, SS, GI and GN) after torsion tests

Table 1. Yield torque T_y, ultimate torque T_u and ultimate angle θ_u of the 4 groups of specimens (CS, SS, GI and GN)

Group	Yield torque T_y (N.m)	Ultimate torque T_u (N.m)	Ultimate angle θ_u (degree)
CS	17.2	30.9	834.2
GI	17.5	31.8	747.7
GN	17.5	31.4	723.1
SS	14.5	30.2	1328.1

Figure 6. show the test specimens that underwent the salt spray test. After only one day of the test, the CS specimen already showed red rust on its surface, whereas GI and GN exhibits white rust formation and no visible change occurred on the surface of the SS specimen. A 100% of red rust covering the surface of the CS specimen took place after two days. Red rust started to develop on the GI specimen after 4 days and the percent covering was gradually increased over time. Following the end of the 18 days of testing (432 hours), the GN and SS specimens were cleared of red rust. The summary of the results is presented in Figure 6.

The relatively high corrosion resistance of the GN bolt should be attributed to the Zn-Ni layer in the coating structure[7], whereas, nickel, chromium, and its corresponding oxide films helps protect the austenitic SS from corrosion.[4] The comparison of the results thus indicates that hot-dip coatings are very helpful for protecting the surface of carbon steel from degradation by corrosion. Hot-Dip coating that provide Zn-Ni interlayers does provide superior protection that is on-par with stainless steel under the condition and the time frame being investigated.



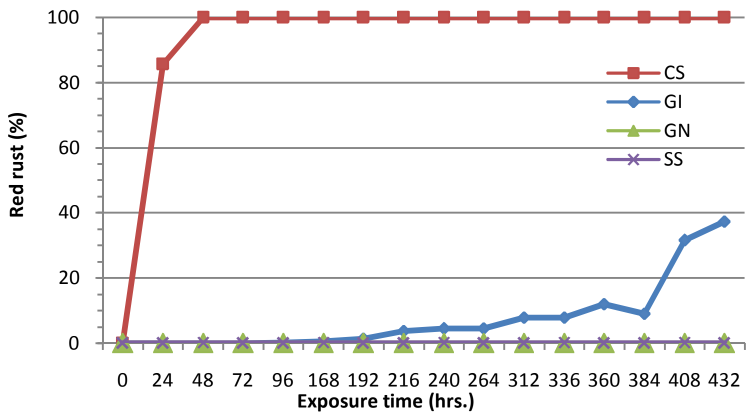


Figure 6. The 4 groups of bolt specimens (CS, SS, GI and GN) exposed to the salt spray condition for 432 hours (a) and percents of red rust present on the surface of the test specimens along the test period (b)

Conclusions

The performance of steel bolts produced by different materials namely, carbon steels (CS), carbon steels that were hot-dipped to form Fe-Zn (GI) and Zn-Ni (GN) protective layers, and 304 stainless steel (SS), was assessed systematically. The CS, GI, and GN showed comparable hardness and torsion behavior under applied loads, suggesting that the coatings do not significantly influence the mechanical response of the core CS material. The SS specimen, on the other hand, showed inferior behavior under torsion with a plateau yielding curve, but exhibited exceptional corrosion resistance under the salt spray test. As the GN specimen showed comparable corrosion resistance to the SS and exhibited similar mechanical response as the CS bolt, the process of hot-dipping to induce a formation of Zn-Ni coating layer is therefore favorable and interesting to be used in the fastening application.

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