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Authors: Sezgin YURTDAŞ, Umut İNCE, Barış TANRIKULU, Cenk KILIÇASLAN, Muhammed Burak TOPARLI

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Corrosion Effects on Fatigue Behavior of Zn-Cr+3 and Zn Flake Coated M8 DIN 933 Bolts

Sezgin YURTDAŞ[1], Umut İNCE[1], Barış TANRIKULU[1], Cenk KILIÇASLAN[1*],
Muhammed Burak TOPARLI[1]

Abstract

In this study, fatigue behavior of Zn-Cr+3 and zinc flake coated bolts was investigated experimentally by considering corrosion effects. Fatigue tests were conducted on M8x50x1.25 8.8 DIN 933 bolts at normal and corroded conditions at force amplitudes between 2.35 and 5.36 kN at test frequency of 75 Hz. A part of bolts was subjected to salt atmosphere for corrosion. According to the Wöhler curves obtained from fatigue tests before corrosion, zinc flake coated bolts showed 1.55 times higher fatigue life compared to Zn-Cr+3. After corrosion, fatigue tests showed that the fatigue life difference increased to 2.10 times for the zinc flake coating. Moreover, corrosion was found to be ineffective on crack initiation region. For both coatings and corrosion conditions, fatigue cracks were seen to initiate from the thread roots.

Keywords: Bolt, fatigue life, coating, corrosion

1. INTRODUCTION

Fasteners are one of the most widely used machine elements in engineering world. They are exposed to various types of external loads and environments. Fatigue under cyclic loading can be considered as the major reason on failure of engineering components. It is estimated that 90% of the mechanical service failures are caused by fatigue [1]. Fatigue life of fasteners depends on many factors such as production method, microstructure, geometry, surface conditions, and coating type. It was shown that inadequate tension and clamping force, fasteners are highly susceptible to fatigue failures [2]. In addition to that, inter-granular cracks in the structure of material was also found to cause fatigue fracture. In another study, the fatigue behavior of the fasteners resulting from corrosion was investigated [3]. According to the experimental results, it was determined that there was a significant fatigue life loss compared to the parts that were not corroded. The previous studies showed that smooth surface conditions in the threads of fasteners and more compressive residual stresses on the surface lead to increase in fatigue strength of the parts [4]. One of the ways to achieve these conditions is to make the threading of the fasteners after the heat treatment process [5-6]. Fatigue tests revealed that fasteners which are threaded after heat treatment showed increased the fatigue life. It was also discussed

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[*] Corresponding author: cenk.kilicaslan@norm-fasteners.com.tr
[1] Norm Cıvata San. ve Tic. A.Ş., AOSB, Çiğli, İzmir, Turkey.
E-mail: sezgin.yurtdas@norm-fasteners.com.tr; umut.ince@norm-fasteners.com.tr; baris.tanrikulu@norm-fasteners.com.tr; burak.toparli@norm-fasteners.com.tr.
ORCID: https://orcid.org/0000-0002-4120-8882; https://orcid.org/0000-0002-3118-3060; https://orcid.org/0000-0001-5441-0118; https://orcid.org/0000-0002-5787-9891; https://orcid.org/0000-0002-5203-5171.

that the type and angle of the thread of the bolts were very important for the fatigue life [7-8]. Specimens with 60° flank angle were found to have higher fatigue life about 20% than those with 90° flank angle. It was also found that the fatigue life of coarse threaded fasteners is higher than that of fine threaded fasteners for bolt sizes of M10 and M24. In another study, bolt length effect was evaluated on the fatigue behavior of joints [9]. Two different bolt lengths were examined and it was shown that increasing bolt length for the same tightening torque increases the joint fatigue strength. The effect of the eccentric cyclic loading on the bolt fatigue life was investigated [10]. It was found that the eccentric load reduced the fatigue life of the bolts and eccentricity did not significantly affect the shape of the cracks. However, a higher mean stress resulted in cracks with a more crescent shape. Considering the fatigue and corrosion behavior of bolts, the effects of corrosion on different threaded elements to investigate bolted joints working in a saline environment was studied [11]. FEM analysis was also carried out to evaluate the stress intensity factor and the change in applied corrosion rate. It was shown that corrosion caused a variation on the surface geometry of the threaded part, leading to a diversity of stress distribution. Corrosion fatigue performance of the high strength bolts were investigated [12]. The crack depth and fatigue life in the corrosion environment of high strength bolts were quantitatively analyzed. The fatigue life of the corroded high strength bolts was reduced by increasing material yield strength, applied tensile and stress amplitude. Stress amplitude had a crucial effect on the fatigue life. As a conclusion, it was shown that the stress amplitude should be controlled at a low level.

Despite there are many investigations on fatigue behavior of fasteners, limited studies concentrating on the corrosion effect of different coating types of fasteners are present in the literature. In this study, M8x50x1.25 8.8 DIN 933 bolts having two different coating types, Zn-Cr+3 and zinc flake, were fatigue tested. Zn-Cr+3 and Zinc flake coated bolts were subjected to salt spray test for 144 and 600 hours respectively until the red corrosion was seen, according to ISO 9227. Then, the effect of coating and corrosion to fatigue life were studied in details.

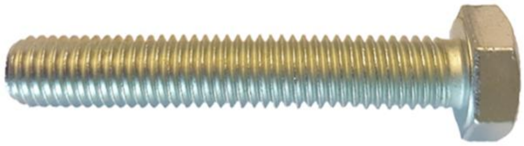
2. MATERIALS AND METHODS

M8x50x1.25 8.8 DIN 933 bolts used in this study were cold-forged in NORM Cıvata, Turkey. The chemical composition of the bolt material, 23MnB4, was given in Table 1. After cold forging, bolts were threaded using flat rolling process. Heat treatment process according to ISO 898-1 “Mechanical properties of fasteners made of carbon steel and alloy steel - Part 1: Bolts, screws and studs with specified property classes - Coarse thread and fine pitch thread” was carried out to obtain 8.8 grade.

Table 1 23MnB4 Chemical Analysis (%Weight).

C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**
0.224	0.941	0.095	0.003	0.011	0.24	0.043
Mo	**Cu**	**Sn**	**Al**	**B**	**Ti**	
0.006	0.039	0.007	0.029	0.003	0.034	

The bolts, obtained from the same batch, are randomly divided into two groups and coated with two different types of coating as Zn-Cr+3 and Zinc flake. Electrolytic zinc plating is one of the most traditional and low-cost coating type for the protection of steel and ferrous metals against corrosion; a thin film layer is formed on the base metal by electrolysis to protect the base metal from corrosion. On the other hand, Zinc flake coatings are cured at comparatively low temperatures, and this type of coating does not contain Cr+6 and therefore, it does not cause hydrogen embrittlement. Contrary to Zn-Cr+3 coating, zinc flake coating process takes place with a binder system. This chemical process requires a firing process. For this reason, the strength of the salt spray test in Zinc flake coating is higher than the zinc coating in the same thickness, according to ISO 9227. Zn-Cr+3 and Zinc flake coated specimens are shown in Figure 1.



(a)

(b)

Figure 1 Specimens; a) Zn-Cr+3 b) Zinc flake.

Fatigue tests were performed according to ISO 3800 "Threaded fasteners-Axial load fatigue testing-Test methods and evaluation of results" standard using Zwick/Roell high frequency fatigue tester. Testing equipment is shown in Figure 2(a). In order to determine the mean force to be applied, 75% of the proof load specified in ISO 898-1 (Mechanical properties of fasteners) was taken as 21.1 kN. Test frequency in all fatigue test, 75 Hz was kept constant. The Wöhler curves for each coating type were determined by means of 36 tests with 6 different applied stress amplitudes. Salt spray test system is shown in Figure 2(b). In this tests, bolts are placed in chamber. NaCl solution is sprayed constantly in the chamber and the atmosphere is controlled by pressured air cycle. The salt spray tests were conducted according to ISO 9227 “Corrosion tests in artificial atmospheres - Salt spray tests” standard.

The macro optical investigations were carried out by employing Zeiss Stemi 508 Streezoom microscope. Images were obtained focusing on the thread root morphology of the bolts to reveal differences between Zn-Cr+3 and Zinc flake coatings. In addition, SEM images were taken by using Carl Zeiss 300 VP to examine fracture surfaces of the bolts after fatigue testing.

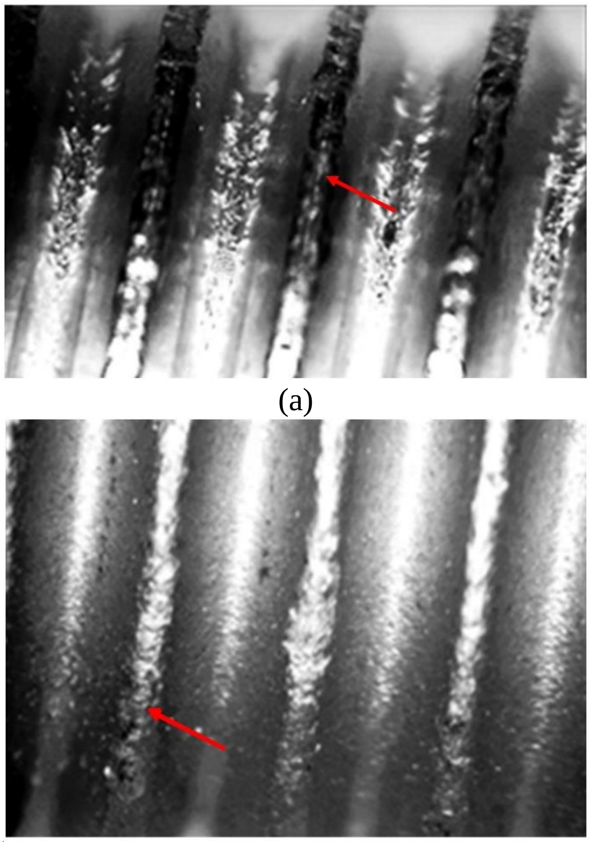
(a)

(b)

Figure 2 Test equipments; (a) Axial load fatigue and (b) salt spray testing chamber.

3. RESULTS AND DISCUSSIONS

After coating operations, bolt threads were examined under microscope since these regions were the most susceptible crack initiation locations. Figure 3(a) and (b) shows Zn-Cr+3 and Zinc flake coated threads, respectively [13]. As seen in the figure, thread roots (depicted with red arrow in the figure) were more homogenously coated in Zinc flake while Zn-Cr+3 coating was seen to have rougher surface.

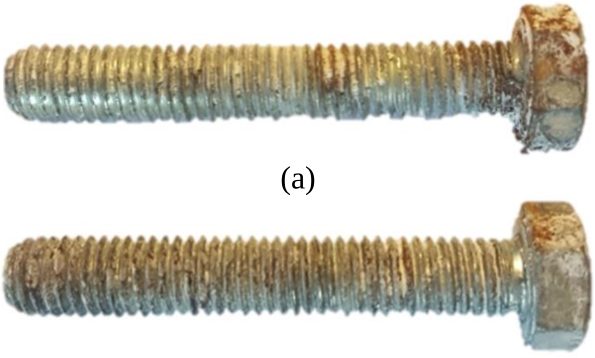


(a)

(b)

Figure 3 Pictures of thread roots; a) Zn-Cr+3, b) Zinc flake [13].

Bolts subjected to salt spray test are shown in Figure 4. As seen in the figure, red corrosion occurred on the bolt surface. Bolt head region was seen to be heavily corroded for Zn-Cr+3 coating while level of red corrosion was more less and uniformly distributed to the shaft region for Zinc flake coating.



(a)

(b)

Figure 4 Bolts after salt spray test; a) Zn-Cr+3 b) Zinc flake. The length of the bolts is 50 mm.

Fatigue tests were carried out before and after salt spray test for both coatings. In all specimens, fatigue cracks occurred at the roots of the threads as seen in Figure 5. Typical fatigue fracture surface of the tested specimens coated with Zn-Cr+3 are given in Figure 5. The failure pattern was very similar for the samples coated with Zinc-flake. A representative SEM image from the fracture surface of the samples can be seen in Figure 6. Considering the geometry of the fatigue zone and instantaneous fracture zone, it was inferred that the applied nominal stress during fatigue testing was low enough for fatigue cracks to initiate and propagate. In addition, based on the morphology of the fatigue zone and instantaneous fracture zone, it was observed that the thread roots acted as stress concentration leading to the fracture surface as given in Figure 5 and Figure 6. Considering the fatigue zone, no clear fatigue striations were observed. For the instantaneous fracture zone, “woody” like morphology, i.e. elongated dimple rupture, was seen.

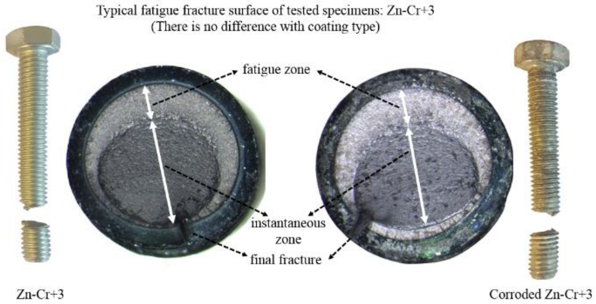


Figure 5 Fatigue fracture surface of the tested specimen; Zn-Cr+3 vs corroded Zn-Cr+3.

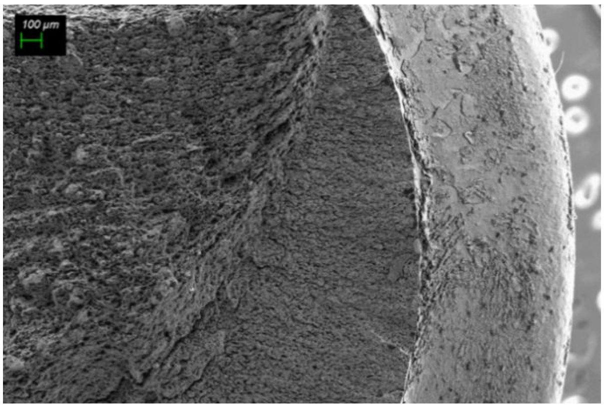
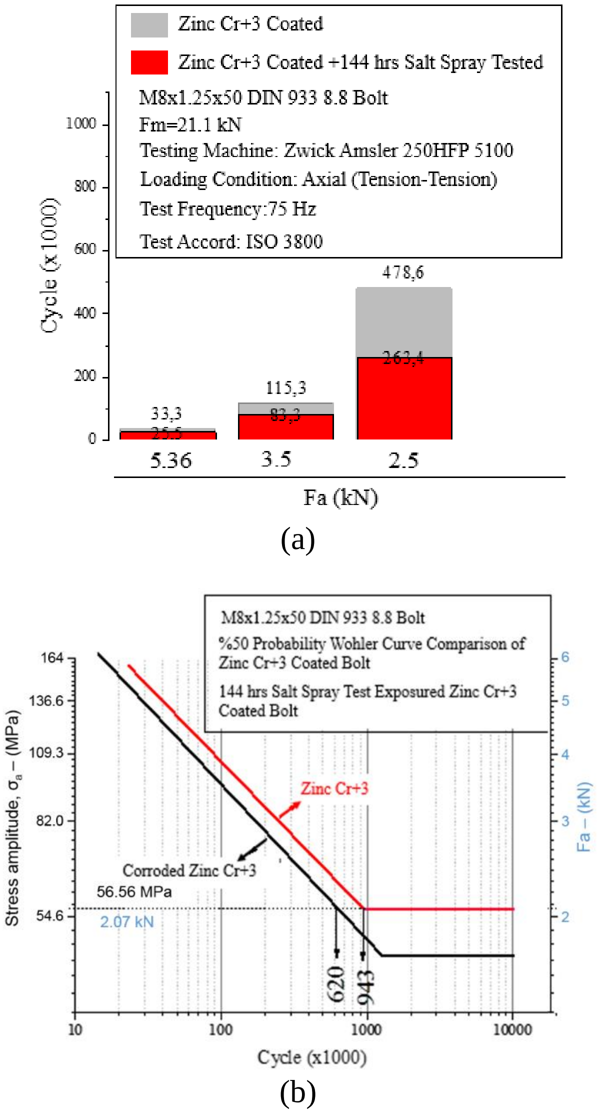


Figure 6 SEM image of fracture surface of the tested specimen.

In Figure 7(a), fatigue life of Zn-Cr+3 coated bolts tested at force amplitudes of 5.36, 3.50 and 2.50 kN were presented. Significant fatigue life reduction was observed after salt spray tests. For force amplitudes of 5.36 kN and 3.50 kN, percent reductions in fatigue life were 23% and 28%, respectively. However, when force amplitude was 2.50 kN, the decrease in fatigue life was 45%. Considering the S-N curves for the Zn-Cr+3 bolts before and after salt spray test, fatigue performance was adversely affected from corrosion (Figure 7(b)). Zn-Cr+3 coated bolts exhibits 1.30 to 1.82 times higher fatigue resistance than 144 hours salt spray tested Zn-Cr+3 coated bolts.

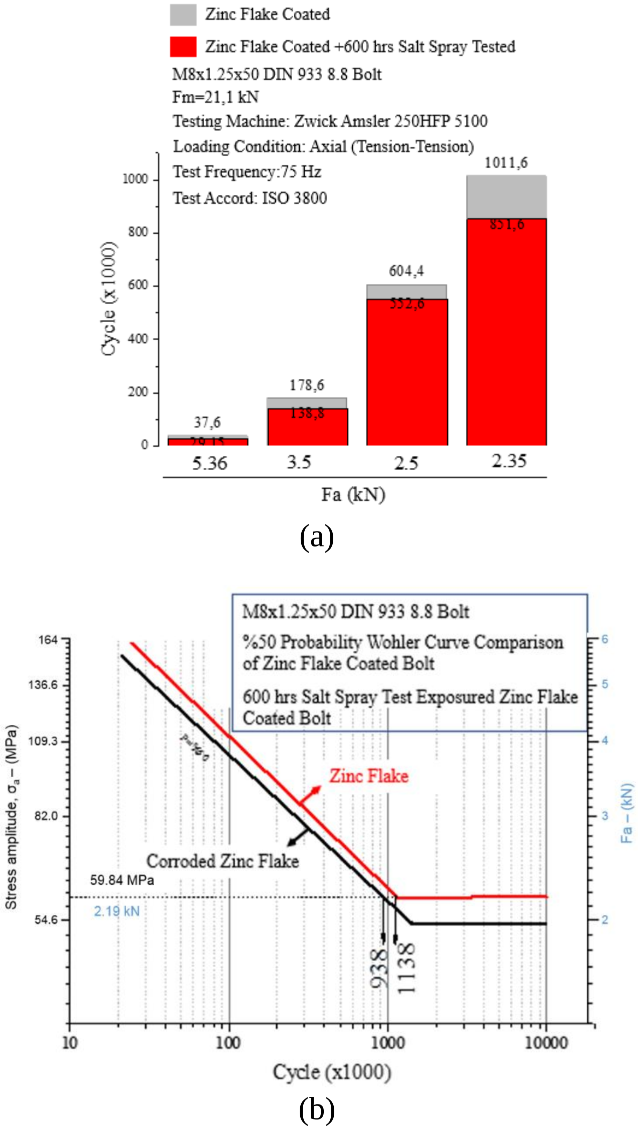


(a)

(b)

Figure 7 (a) Fatigue tests results and (b) Wöhler curves of Zn-Cr+3 coated bolts before and after salt spray tests.

In Figure 8(a), fatigue life of Zinc flake coated bolts tested at force amplitudes of 5.36, 3.50, 2.50 and 2.35 kN were introduced. As for Zn-Cr+3, remarkable fatigue life degradation was find after salt spray tests. For force amplitudes of 5.36 and 3.50 kN, decrease in fatigue life was found as 23%. When force amplitude was decreased to 2.50 and 2.35 kN, decrease in fatigue life was 9% and 16%, respectively. Considering the S-N curves for the Zinc flake bolts before and after salt spray test, fatigue performance was adversely affected from corrosion (Figure 8(b)). Zinc flake coated bolts exhibits 1.09 to 1.29 times higher fatigue resistance than 600 hours salt spray tested Zinc flake coated bolts.

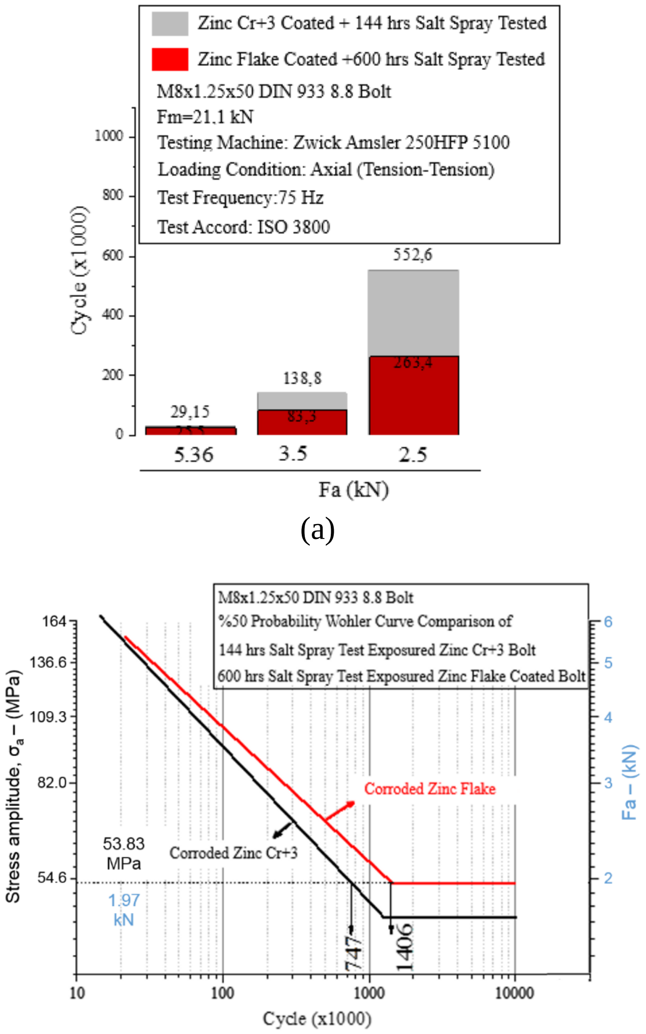


(a)

(b)

Figure 8 (a) Fatigue tests results and (b) Wöhler curves of Zinc flake coated bolts before and after salt spray tests.

Considering fatigue life of coated bolts before and after salt spray tests, Zinc flake coated bolts showed higher number of cycles compared to Zn-Cr+3 (Figure 9) though salt spray testing was conducted for 144 and 600 hours for Zn-Cr+3 and zinc flake, respectively. The difference was more significant as the force amplitude of fatigue tests were increased; i.e. Zinc flake bolts showed 1.1, 1.7 and 2.1 times higher fatigue performance for the force amplitude of 5.36, 3.50 and 2.50 kN, respectively.



(a)

(b)

Figure 9 Comparison of (a) Fatigue tests results and (b) Wöhler curves of Zinc flake and Zn-Cr+3 coated bolts after salt spray tests.

Fatigue life of corroded Zinc flake coated bolts were compared to plain Zn-Cr+3 coated bolts in Figure 10. As depicted in the figure, fatigue life of both bolts were found to be similar. Main reason of that can be attributed to the difference in coating process of Zn-Cr+3 and zinc flake. Zn-Cr+3 coating is based on electrolytic bonding between the coating and the substrate. However, zinc flake coating is non-electrolytically applied. Since, zinc plating is an electrolytic proses, surface roughness is higher compared to zinc flake coating. As discussed in the literature [14-17] depending on the conditions, surface roughness can act as a stress concentrator and lead to premature crack initiation leading fractures due to fatigue. Therefore, fatigue performance was higher for zinc flake coating having better surface finish compared to Zn-Cr+3 plating.

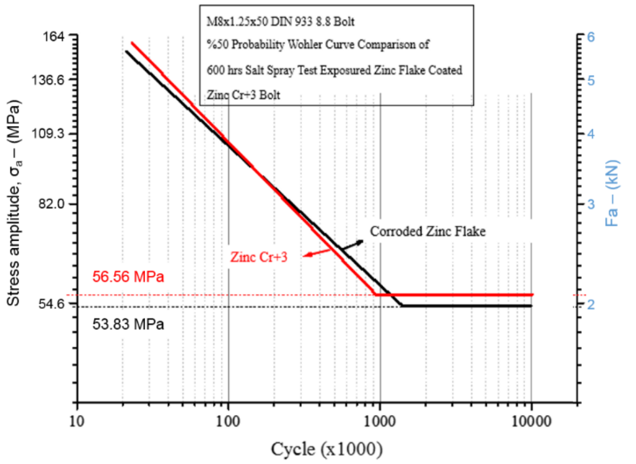


Figure 10 Fatigue life comparison of Zinc flake bolts after corrosion test and Zn-Cr+3 coated bolts.

4. CONCLUSIONS

In this study, fatigue behavior of Zn-Cr+3 and zinc flake coated bolts was investigated experimentally by considering corrosion effects. Based on the results, following conclusions can be drawn:

- Zinc flake coated bolts showed higher fatigue resistance compared to Zn-Cr+3 coated bolts. This phenomenon can be explained by effect of porous morphology of thread roots of Zn-Cr+3 coated bolts. This porous morphology can act as a trigger for crack initiation leading to lower fatigue resistance. Another factor contributing to fatigue performance difference can be incorporated with the higher coating thickness of zinc flake leading to higher radius on thread root and decrease in stress concentration at possible crack tips.
- As a result of comparison of Wöhler curves of corroded bolts, corrosion lowers the fatigue resistance of both coating type. However, negative effect of corrosion on fatigue life of Zn-Cr+3 coated bolts was higher than Zinc flake coated bolts.
- 600 hours salt spray tested Zinc flake coated bolts and non-salt spray tested Zn-Cr+3 coated bolts exhibit similar fatigue

resistance. Therefore, it can be concluded that zinc flake coated bolts have significantly higher resistance to corrosion fatigue compared to Zn-Cr+3 coated bolts.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

Sezgin YURTDAŞ and Umut İNCE designed the research idea and carried out the experimental work. Barış TANRIKULU, Cenk KILIÇASLAN and M. Burak TOPARLI conducted literature survey and contributed to experimental work and data analyses. All authors participated in discussions of results and manuscript preparation.

The Declaration of Ethics Committee Approval

The authors declare that this document does not require an ethics committee approval or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the article and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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