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Comparing of High-Cycle Fatigue Lifetimes in Un-corroded and Corroded Piston Aluminum Alloys in Diesel Engine Applications

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Abstract

Diesel engine components in the combustion chamber have been exposed to cyclic loadings under environmental effects, including high temperatures and corrosive fluids. Therefore, knowing the corrosion-fatigue behavior of materials is essential for designer engineers. In this article, pure fatigue and corrosion-fatigue behaviors of the piston aluminum alloy have been experimentally investigated. For such an objective, as-cast and pre-corrosive standard samples were tested by the rotary bending fatigue machine, under 4 stress levels. Some specimens were exposed to the corrosive fluid with 0.00235 % of the sulfuric acid for 100 and 200 hours. The results showed higher weight losses for 200 hours immersion times. As another result, it could be concluded that the lifetime decreased in pre-corrosive samples for both 100 and 200 hours of the immersion time, compared to that of as-cast specimens. However, such a lifetime reduction was more significant for 200 hours of the immersion time, especially within the high-cycle fatigue regime (or lower stress levels). Under high stress levels, both pre-corrosive sample types had almost similar behaviors. The field-emission scanning electron microscopy images of specimen fracture surfaces indicated that the brittle region of the fractured surface was larger for specimens after the 200 hours of corrosion-fatigue testing than the other specimen.

Keywords: Bending fatigue, Corrosion-fatigue, Piston aluminum alloys, Immersion times, Diesel engines

1. Introduction

Nowadays, aluminum alloys have been vastly utilized in engine and automotive industries. Diesel engine components in the combustion chamber have been exposed to cyclic mechanical loadings. Moreover, they are affected by the environment, including high temperatures and corrosive fluids. For engineers, it is essential to know the corrosion-fatigue behavior of the material, used in engines parts.

In the following paragraphs, a literature review could be seen for such a topic on fatigue testing of aluminum alloys. Li et al. [1] studied the influence of the heat treatment on the microstructure and mechanical properties of the Al10Mg2Si aluminum alloy. the They found that the eutectic Mg_2Si phase in the matrix transformed from long rods to short fibers and also spherical morphologies, after solutioning at 520 °C for 6 hours and also ageing at 200 °C for 6 hours. Enhancing the hardness and the tensile strength was due to fine eutectic Mg_2Si phases, combined with nano-sized precipitates. Wang et al. [2] presented low-cycle fatigue behaviors and the lifetime estimation of piston aluminum alloys at elevated temperatures. Their results demonstrated cyclic softening for the material at high temperatures. Fatigue cracks usually initiated from the silicon phase and then grew along particles at low temperatures. Increasing the temperature caused the ductile tearing fracture behavior, through micro-cracks. Azadi [3] performed thermo-mechanical fatigue experiments to find the effect of the heat treatment on the material behavior of A356.0 aluminum alloys and AZE911 magnesium alloys. His results depicted no effective difference in the thermo-mechanical fatigue behavior of as-cast and heat-treated aluminum alloys, at 250 °C. The reason was over-ageing in the alloy.

For the second part of reviewing articles, in the following paragraphs, a survey could be seen for the corrosion-fatigue behavior of aluminum alloys. Guerin et al. [4] studied fatigue behaviors of 2050 aluminum-copper-lithium alloys, with T34 and T84 heat treatments. Their results were presented for the initial samples and pre-corroded specimens in the 0.7 NaCl environment. Fatigue lifetime tests in the air on pre-corroded samples revealed a significant decrease in fatigue lifetime, related to the presence of corrosion defects before the cyclic condition. A strong effect of first minutes of the immersion in the corrosive media was evidenced on fatigue lifetime behavior. Fatigue-corrosion tests revealed that the T34 metallurgical state was more affected by the fatigue-corrosion phenomenon in terms of the fatigue lifetime than the T84 metallurgical state. This observation could be explained by the increased propagation of the intergranular corrosion, enhanced by the cyclic condition. Chen et al. [5] studied the influence of the pre-deformation on the pre-corrosion multiaxial fatigue behavior of the 2024-T4 aluminum alloy. Pre-damages, containing pre-deformation and pre-corrosion damages, had effects on multiaxial fatigue properties. Their results indicated that under similar pre-deformation levels, when the pre-corrosion time enhanced, the multiaxial fatigue lifetime reduced. Since on the sample surface, pitting due to the corrosion was seen as the potential place for the crack initiation. The fracture analysis demonstrated that the synergistic combination of pre-deformation and pre-corrosion damages was significant than that of separated initial damages. The cyclic softening behavior was observed in the tangential direction. Chen et al. [6] investigated the multiaxial fatigue behavior of 2024-T4 aluminum alloys under different corrosion cases in the NaCl corrosive environment. They showed that by increasing the pre-corrosion time from 0 to 8 days, under 330 MPa of the stress, the multiaxial fatigue lifetime of the material reduced from 32,665 to 13,595 cycles. The reason could be mentioned as corrosion pits, which could be seen on the sample surface. Then, the number and the size of pits were higher at higher pre-corrosion times. Therefore, cracks initiated on the sample surface and propagated into the inside region of the specimen. Moreover, the cyclic hardening behavior could be observed under both axial and tangential directions.

Chen et al. [7] illustrated the influence of alternate corrosion factors on the multiaxial low-cycle fatigue lifetime of 2024-T4 aluminum alloys, with the application of aircrafts. Factors included the alternate corrosion time, the corrosion temperature, the corrosion environment flow rate and the pH value. The effect of these mentioned factors was revealed on the fatigue strength of the material. The multiaxial fatigue lifetime reduced, when the alternate corrosion time, the corrosion temperature and the corrosion environment flow rate increased. This result was reversed for the pH value. Rodriguez et al. [8] founded the corrosion effect on the fatigue performance of dissimilar friction stir welding of high-strength AA6061-to-AA7050 aluminum alloys. The pre-corrosion damage was done on the crown surface of welding by the immersion in the 3.5% NaCl environment for different exposure times. Their results revealed that the initial damage was due pitting, which decreased the fatigue lifetime, as the region of the crack initiation. Moreover, higher corrosion damage was detected in the AA7050 alloy, compared to that of the AA6061 alloy. Failures were seen as the crack propagation in AA6061 under high-strain amplitudes (>0.3%) and the crack growth in AA7050 under low-strain amplitudes (<0.2%). The reason was cyclic strain hardening in the material at the tip of corrosion pits. Mishra [9] studied the effect of the pre-corrosion on mechanical properties and the fatigue lifetime of 8011 aluminum alloy. After 100 hours of the pre-corrosion in a corrosive environment, their results depicted that corrosion pits on the sample surface led to the crack initiation. Under 120 MPa of the bending stress, the fatigue lifetime of the initial specimen was double of the corroded sample. Moreover, the fracture behavior was ductile, based on dimple marks.

In this research, the evaluation of bending fatigue properties for corroded piston aluminum alloys was done and reported in figures. The fracture surface was also examined to find damages mechanisms.

2. Descriptions of materials and experiments

In this article, the studied material was aluminum-silicon alloy (AlSi12CuNiMg), which has been vastly used in the piston of automotive engines. The chemical composition of this material was shown in Table 1.

The fabrication technique of the alloy for high-cycle fatigue testing was the gravity casting approach, which is shown in Figure 1. Then, all standard samples were gravity-casted in the cast-iron mold. Moreover, all these casted cylinders were quenched in the air at 23 °C of the temperature, after the casting process.

For fabricating standard cylindrical samples, aluminum bars or ingots were initially melted. As a note, no master alloys were added. The melt was held for 2 hours at 700 °C of the temperature [10]. It is worth noting that in the casting process, the mold temperature was kept constant at 265 °C with a deviation of 10 °C [10]. In order to minimize the presence of any foreign objects in the melt that causes cavities or pores, after the melt has reached to a stable temperature in the mold, degassing and removing the slag were performed using the argon gas and special tablets. And also, it should be noted that all casting tools were coated and preheated before starting the casting process. The casting mold, which was used in this research, is shown in Figure 2. More details of casting could be found in the literature [10].

The fully-reversed bending loading condition (R=-1) was applied on standard samples for high-cycle fatigue testing with a three-point rotary bending fatigue testing device (entitled SFT-600 fabricated by the SANTAM Company). This device is shown in Figure 3. The bending stress (120, 150, 180, 210 MPa) was controlled under cyclic loadings. This was done through the high-cycle fatigue regime, based on the ISO-1143 standard [11].

For corrosion-fatigue tests, samples were pre-corroded in the 0.00235% H_2SO_4, which was based on the maximum sulfur gasoline in diesel engines [12] for 100 and 200 hours [9,12]. Due to consider the diesel engine application in this article, the environment type is almost different from the literature [4,6,8], where the NaCl environment influence was studied. Standard specimens after and before the pre-corrosion process are depicted in Figure 4. The sample after the pre-corrosion seemed to be darker, compared to the initial specimen**.**

Table 1.
Elements in the chemical composition of the studied aluminum-silicon alloy in the piston application

Elements	Al	Si	Fe	Cu	Mg	Ni	Zn	Mn
Percent (%)	Base	12.70	0.56	1.16	1.00	0.80	0.16	0.12


Fig. 1. The gravity casting procedure of initial samples


Fig. 2. The geometry of the casting mold

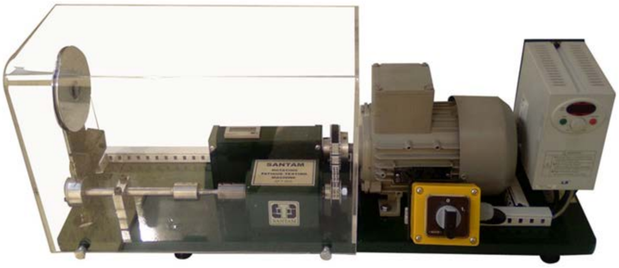

Fig. 3. The rotary bending fatigue test machine

Fig. 4. Fatigue test samples, including before (the above one) and after (the bottom one) the pre-corrosion process

Before fatigue testing, microstructures were examined by the Olympus model optical microscopy. For such an objective, a polishing process was firstly performed on specimens and then, a Keller etchant (the environment including 95 ml H_2O, 2.5 ml HNO_3, 1.5 ml HCL and 1.0 ml HF) was utilized [13-15]. To study the fracture surface, the field-emission scanning electron microscopy was also used to find the failure mechanism under bending cyclic loadings.

3. Descriptions of achieved results

As a first result, the microstructure of aluminum-silicon alloys, before fatigue testing, could be seen in Figure 5. Based on this figure, the dominated phase was α-Al as the matrix [12]. The silicon phase was as a major precipitate, dispersed in the aluminum matrix, and observed in two shapes, blocky and Chinese-script morphologies [12,14-16]. Another precipitate consisted of an intermetallic phase that was the (Al,Cu) phase. This phase was seen in a brown-color area. Another intermetallic phase was (Al,Ni) with a black-colored area. Similar phases have been reported in the literature [14-19].

The image of the field-emission scanning electron microscopy from corroded surfaces for aluminum-silicon alloys after 200 hours of the immersion time in the acidic environment before fatigue testing is shown in Figure 6. Besides this microscopic image, as it could be also seen in Figure 4, some macroscopic pits could be seen on the sample surface due to the corrosion phenomenon. These sites have potentials for the crack initiation under cyclic bending loadings.

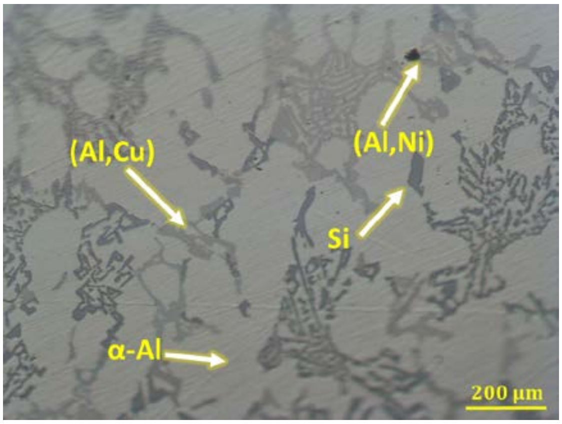

Fig. 5. The material microstructure with the optical microscopy, before fatigue testing

Corrosion reactions that contained anodic (the dissolution of Al atoms) and cathodic (the evolution of hydrogen ions) reactions caused pits, holes and the cracks formation on the surface of samples. The initiation of such defects could be from precipitate/matrix boundaries [20]. In these areas, the micro-galvanic corrosion would be also happened due to lower strength of the alloy. It seemed that some pits were connected together and formed a larger hole in some areas of the sample surface.

In Figure 7, the fatigue lifetime is depicted plus the corrosion-fatigue lifetime of aluminum alloys. In this figure, the weight loss is also shown after two immersion times for the piston aluminum alloy, before fatigue testing. This test indicated a higher weight loss for specimens after 200 hours of the immersion time, compared to the other time. The weight loss of specimens increased by about 60%, when the immersion time increased as 2 times. This event showed a nonlinear behavior of the corrosion rate for the utilized aluminum alloy in the 0.00235% H_2SO_4 environment. The higher exposure time caused more corrosion reactions. Therefore, the dissolution of more aluminum atoms in the acidic environment occurred on the surface of specimens.

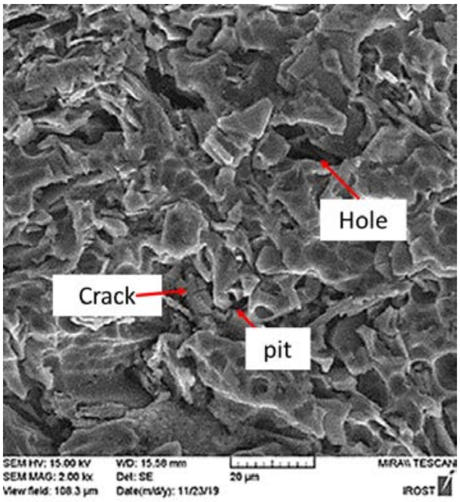

Fig. 6. The microscopic image of corroded surfaces for aluminum alloys under 200 hours before fatigue testing [12]

As another result, it could be concluded that the lifetime decreased in pre-corrosive samples for both 100 and 200 hours of the immersion time, compared to that of as-cast specimens. Such as this result was reported by Guerin et al. [4] for 2050 aluminum-copper-lithium alloy, pre-corroded in the 0.7 NaCl environment.

However, such a lifetime reduction was more significant for 200 hours of the immersion time, especially within the high-cycle fatigue regime (or lower stress levels). Under high stress levels, both pre-corrosive sample types had almost similar behaviors. Under 120 MPa of the stress level, the reduction of the fatigue lifetime in immersion time of 100 hours was 66.8%. Under 210 MPa, such a decrease was more as 85.9%. These reductions in the fatigue lifetime for the immersion time of 200 hours were 96.2% and 77.1%, respectively under 120 and 210 MPa.

These results were in an agreement with obtained results of the literature [5] for 2024-T4 aluminum alloy. Chen et al. [5] mentioned that corrosion pits induced a stress concentration on the sample surface, which could be a potential location for initiating fatigue cracks, under bending loading. It should be noted that Aroo et al. [12] claimed that the corrosion rate was not sensitive to the acid amount. However, the corrosion rate decreased by increasing the immersion time.

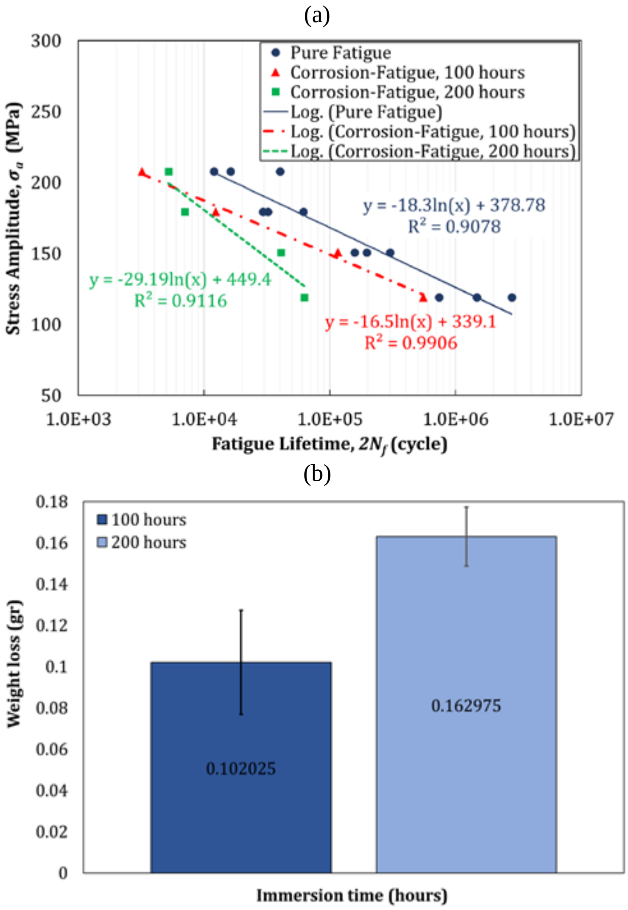

Fig. 7. (a) The stress amplitude versus the fatigue and the corrosion-fatigue lifetime and (b) the weight loss versus the immersion time, obtained for the piston aluminum alloy

Images of the field-emission scanning electron microscopy from fracture surfaces are shown in Figure 8. Cleavage marks plus micro-cracks could be seen on the fracture surface of samples. These pictures showed that the brittle region of the fractured surface was larger for specimens after with 200 hours of the immersion time and the corrosion-fatigue test than the other sample. In addition, more defects including corrosion pits were found on this surface of this specimen. Such defects caused a reduction in the fatigue lifetime. A similar observation was shown by Mishara [9]. It was found that after 100 hours, as the pre-corrosion time, the corrosion pit was formed on the surface of 8011 aluminum alloy. These defects initiated the fatigue crack propagation and decreased the fatigue lifetime of the alloy [9].

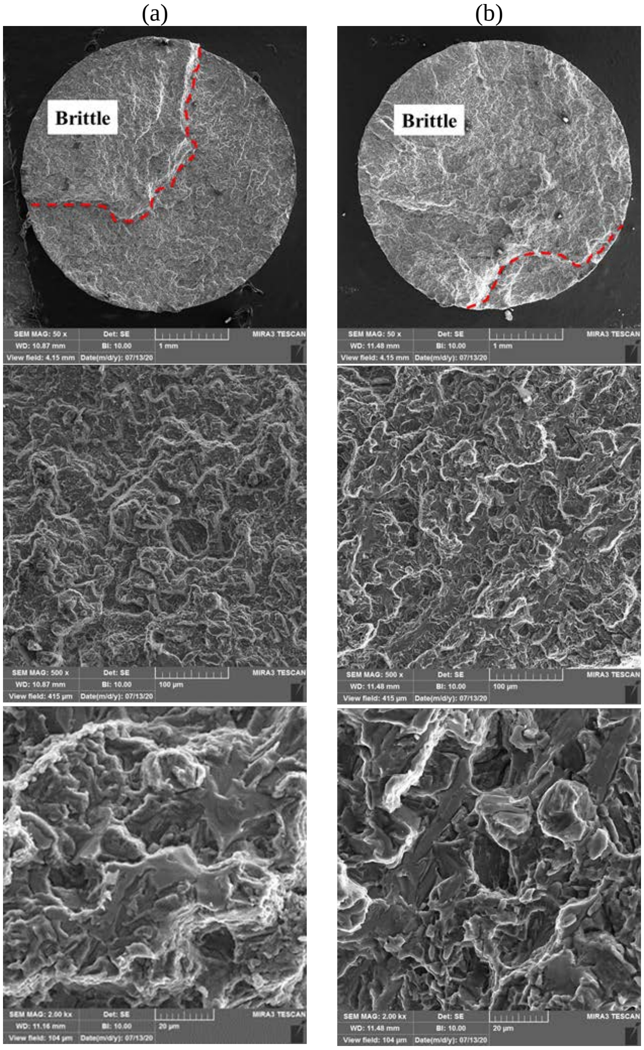

Fig. 8. The image of the field-emission scanning electron microscopy from fracture surfaces for aluminum-silicon alloys under 150 MPa stress level for (a) the pure fatigue test and for (b) the corrosion-fatigue test

When the value of the bending stress was 120 MPa, the lifetime of the un-corroded sample increased about 2 times compared to the pre-corroded specimen [9]. Moreover, after 100 hours of the pre-corrosion, at the same value of the bending stress, the fatigue lifetime of the un-corroded specimen was almost 3 times higher than that of the corroded one.

4. Conclusions

In this article, pure fatigue and corrosion-fatigue behaviors of piston aluminum alloys after 100 and 200 hours of the immersion time in the 0.00235% H_2SO_4 were studied. Experimental data could be described and listed as follows,

- The fatigue lifetime decreased in pre-corrosive samples for both 100 and 200 hours of the immersion time, compared to that of as-cast specimens. Higher weight losses were observed for 200 hours of the immersion time, compared to 100 hours of the immersion time.
- The fatigue lifetime reduction was more significant for 200 hours of the immersion time, especially within the high-cycle fatigue regime (or lower stress levels). This reduction of the fatigue lifetime was 66.8% and 96.2%, respectively for 100 and 200 hours of the immersion time, under 120 MPa.
- As an interesting result, under high stress levels, both pre-corrosive sample types after 100 and 200 hours had almost similar fatigue behaviors. It means that the immersion time had almost no effects on the fatigue lifetime under 210 MPa.
- The field-emission scanning electron microscopy image of fracture surface demonstrated that the brittle region of the fractured surface was larger for specimens after the 200 hours of the immersion time and the corrosion-fatigue test than the other specimen. In addition, more defects including corrosion pits were found on this surface. Such defects caused a reduction in the high-cycle fatigue lifetime.

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