Influence of Hydrogen on Fatigue Property of Suspension Spring Steel with Artificial Corrosion Pit after Multi-step Shot Peening

Manabu KUBOTA,1)* Takahisa SUZUKI,2) Daisuke HIRAKAMI3) and Kohsaku USHIODA4)


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In order to reduce the weight of the suspension springs by increasing the strength level of the steels used, improvement of the corrosion fatigue property is the most important issue. This study investigated, the effect of residual stress, artificial corrosion pit depth and diffusible hydrogen on rotary bending fatigue properties of specimens after double shot and triple shot peening. The following conclusions were obtained:

1) Fatigue limits of specimens having the artificial corrosion pit of 250 μm depth with and without the charged hydrogen are improved remarkably by the triple shot peening.
2) Fish-eye fatigue fracture with an inclusion as the fatigue crack initiation site occurs frequently due to the charged hydrogen.
3) A good relationship between fatigue limit after shot peening and compressive residual stress at the bottom of the artificial corrosion pit is obtained regardless of the depth of the artificial corrosion pit.

KEY WORDS: high strength low alloy steel; corrosion fatigue; shot peening; residual stress; hydrogen; fish-eye fatigue fracture.

1. Introduction

In order to reduce the weight of a suspension spring, which is used for automotive suspension system by reducing the diameter of the spring wire, the design stress of the spring has to be increased. A major cause of fracture of suspension spring is related to fatigue fracture.1) Therefore, in order to increase the design stress of the spring, it is effective to increase the fatigue strength of spring steel. Generally, in order to increase the fatigue strength of steel, it is effective to increase the strength level of steel. However, it is considered that the corrosion fatigue phenomenon becomes remarkable with an increase in the strength level of the steel. Therefore, the corrosion fatigue phenomenon is one of the problems which should be overcome.

The present authors focused on prior-austenite grain size, corrosion pit, residual stress induced by shot peening and hydrogen embrittlement as factors which affect the corrosion fatigue of suspension spring steel in the previous studies Where a comprehensive investigation was carried out to reveal the mechanism of the corrosion fatigue phenomenon of the suspension spring.2,3) Thereby, it was revealed that the relationship between the corrosion pit depth and residual stress distribution was very important. That is, in the case of a specimen without a corrosion pit or with only shallow corrosion pits having still large compressive residual stress at the bottom of the pits, the fatigue property was fairly good but declined with an increase in the diffusible hydrogen content. On the other hand, in the case of a specimen with a deep corrosion pit having only small compressive residual stress, the fatigue strength decreases remarkably regardless of the diffusible hydrogen content. The decrease rate of the fatigue strength due to a decrease in the compressive residual stress at the bottom of the corrosion pit was larger than that due to an increase in diffusible hydrogen. That is, diffusible hydrogen is a dominant factor in the decline of the fatigue strength when there is no corrosion pit or only a shallow corrosion pit. Takahashi et al. revealed that the compressive residual stress makes an artificial corrosion pit harmless.4) From our conclusions, the importance of their result was confirmed.2,3) The previous result above-mentioned suggest that the induction of a large and deep residual stress distribution to a surface layer is the most effective measure to improve the corrosion fatigue strength of the suspension spring.

According to the previous study where the shape of the actual corrosion pit of automotive suspension coil springs...
was investigated,\textsuperscript{5} the majority of corrosion pits had a diameter/depth ratio of approximately 2, whereas there were few corrosion pits that had the diameter/depth ratio of below 1; the majority of the corrosion pits were U shaped. The average value of the maximum corrosion pit depth of all investigated coil springs were approximately 150 \textmu m, and the maximum corrosion pit depth was 250 \textmu m. This maximum corrosion pit depth is approximately equal to the depth of a compressive residual stress layer which is induced by a general shot peening condition. Therefore, it is considered that the fatigue strength of the suspension spring decreases due to the formation of the corrosion pit. In other words, it is expected that the corrosion fatigue property of the suspension spring can be improved by deepening the compressive residual stress layer. It is widely known that the fatigue property of mechanical parts can be improved by a large and deep compressive residual stress\textsuperscript{6–8} and that the fatigue property of the suspension spring can be improved effectively by increasing the compressive residual stress at a surface.\textsuperscript{9,10} On the other hand, according to the previous studies\textsuperscript{2,3} by the present authors, it is expected that the corrosion fatigue property of the suspension spring can be improved by increasing the compressive residual stress at the surface to ameliorate the corrosion fatigue property of the suspension spring. However, there are few studies which have satisfactorily investigated the relationship between the compressive residual stress and the corrosion fatigue property of the suspension spring.

In this study, the effects of the artificial corrosion pit and the diffusible hydrogen on the fatigue property of the specimens having a deeper compressive residual stress layer using a multi-step shot peening process than the conventional one was investigated. Then, the beneficial effect of increasing the depth of the compressive residual stress on the corrosion fatigue property was evaluated.

2. Experimental Procedure

2.1. Specimens

The steel used in this study is the SAE9254, which is one of the most popular steels used for the automotive suspension coil spring and was also used in the previous studies.\textsuperscript{2,3} The chemical composition of the steel is shown in Table 1. The steel was hot-rolled wire rod with 13 mm in diameter. Then, it was quenched and tempered in a laboratory to obtain a tempered martensitic structure. The condition of heat treatment, prior-austenite grain size, and mechanical properties of the specimens are shown in Table 2.

A schematic illustration of the specimen for the rotary bending fatigue test is shown in Fig. 1. The preparation procedure of the fatigue test specimens is described in Fig. 2. The specimens were made by machining, and then, the parallel and round portion of the specimens were polished along the longitudinal direction by an emery paper. After that, multi-step shot peening under several conditions described in section 2.2 were carried out to the parallel and round portion of the specimens.

2.2. Multi-step Shot Peening

The conditions of multi-step shot peening are described in Table 3. The impeller-type shot peening machine was used. The conditions of shot peening used in this study were the conventional double shot peening and a triple shot peening, which were newly examined in this study. The size of the first media of triple shot peening was 1.7 mm in diameter to obtain a deeper compressive residual stress distribution. The residual stress at the center of the parallel portion of a fatigue specimen was measured by the micro-area X-ray residual stress measurement system (AutoMATE, Rigaku Corp.) with side inclination method (X-ray tube with Cr anode, $2\theta = 156.4^\circ$). The measurement direction of the residual stress was the longitudinal direction of the specimen. The residual stress distribution as a function of depth was measured by polishing the specimen electrically. The surface roughness of the specimens before and after shot peening was measured by the surface roughness measuring instrument (Surfcoorder SE3500, Kosaka Ltd.).

2.3. Artificial Corrosion Pit

Artificial corrosion pits were produced to the some
specimens by electric discharge machining. The number of artificial corrosion pits was one per specimen, and the pit was located at the center of the specimen. The artificial corrosion pits were cylindrical holes of 1 mm in diameter. A schematic illustration of the artificial corrosion pits is shown in Fig. 3. The depths of the pits were 250 μm, which corresponds to an observed maximum corrosion pit depth in actual automotive coil springs, and 500 μm.

2.4. Fatigue Test

The rotary bending fatigue test was conducted using the specimens prepared as described in sections 2.1–2.3. The rotational speed in the test was 2 000 rpm, and the maximum number of cycles was $10^7$. Fracture surfaces of the specimens were observed by SEM (scanning electron microscopy).

2.5. Fatigue Test after Hydrogen-charging

Hydrogen-charging was carried out to some fatigue specimens. The procedure of the fatigue test is shown in Fig. 4. Concerning the condition of hydrogen-charging, zinc plating was exploited to prevent hydrogen-discharging from the surface of the specimens. The method to measure the diffusible hydrogen content in this study is the same as that used in the previous study. The specimens were held at room temperature after hydrogen-charging and zinc plating for making hydrogen distribution homogeneous through the cross-section of the specimens. Then, the fatigue test was carried out. The aimed diffusible hydrogen content, which was charged into the specimens, was 0.6–0.9 ppm. The diffusible hydrogen content in the specimens was measured by the procedure as follows. The specimens were retrieved from the testing machine immediately after the fatigue test, and the parallel portion of a specimen was taken by a wet cutting machine; the zinc plating was removed from the specimen by an electrochemical method. The diffusible hydrogen content was measured by TDS (thermal desorption spectrometry), which utilizes a gas chromatograph. The heating rate was 100 K/h. Diffusible hydrogen is defined as hydrogen which is discharged from room temperature to 473 K.

3. Result

3.1. Residual Stress Distribution

The residual stress distributions of the specimens subjected to the double and triple shot peening processes are shown in Fig. 5. The residual stress at the surface and maximum residual stress of each specimen was almost the same, irrespective of the number of shot peening. On the other hand, the layer having a large compressive residual stress in the triple shot peened specimen was much deeper than that in the double shot peened one.

3.2. Effects of Residual Stress Distribution and Artificial Corrosion Pit Depth on Fatigue Strength of Hydrogen-uncharged Specimens

The S-N curves of hydrogen uncharged-specimens are shown in Fig. 7. The fatigue limits of the double and triple shot peened smooth specimens were almost the same, and several fish-eye fracture surfaces were observed nearby.
the inclusion as the fatigue crack initiation site (Fig. 7(a)).

Figures 8 and 9 show the fracture surfaces of the double and triple shot peened specimens, respectively. They fractured from the inclusions as the fatigue crack initiation site. The inclusions of several tens of μm in diameter were observed at the fatigue crack initiation site. The inclusions were located at 300 μm and 560–930 μm deep from the surface in the fracture surface of the double and triple shot peened specimens, respectively. These results indicate that the inclusion located at the deep layer where large compressive residual stress no longer exists is the initiation sites of fatigue crack of the double and triple shot peened specimens. Observations of the fracture surface by optical microscopy were conducted separately. There was no ODA (optical dark area) around the inclusion as the fatigue crack initiation site.

The fatigue limit of the double shot peened specimen having the artificial corrosion pits of 250 μm deep decreased by 61% compared with the smooth specimen, as shown in Fig. 7(b). On the other hand, the fatigue limit of the triple shot peened specimen having the same artificial corrosion
pit depth only decreased by 16% compared with the smooth specimen. Therefore, it is considered that the triple shot peening improves the fatigue limit of the specimens having deep artificial corrosion pits. All the fatigue crack initiation sites were at the bottom of the artificial corrosion pits, as shown in Figs. 10 and 11. The fatigue limit of the shot peened specimen having the artificial corrosion pits of 500 μm deep decreased significantly compared with the smooth specimen, regardless of the number of shot peening, as shown in Fig. 7(c). All the fatigue crack initiation sites were at the bottom of the artificial corrosion pits.

Figure 12 shows the fatigue limits determined by data in Fig. 7 and in the previous study 2) as a function of the artificial corrosion pit depth. It is clearly shown that the decrease of the fatigue limit can be prevented by applying triple shot peening instead of double shot peening.

3.3. Effects of Residual Stress Distribution and Artificial Corrosion Pit Depth on Fatigue Strength of Hydrogen-charged Specimens

The S-N curves of the hydrogen-charged specimens are shown in Fig. 13. Similar to the result of the fatigue test
without hydrogen-charging, the fatigue limits of the double shot peened and triple shot peened smooth specimens exhibited almost the same value (Fig. 13(a)). The fatigue limits of the double and triple shot peened smooth hydrogen-charged specimens decreased by 20% compared with the fatigue limits of the hydrogen-uncharged specimens. Moreover, the fish-eye fatigue fracture surface with an inclusion was observed as the fatigue crack initiation site.

The fatigue limit of the double shot peened specimen having the artificial corrosion pits of 250 µm deep decreased by 57% compared with the smooth specimen, as shown in Fig. 13(b). On the other hand, the fatigue limits of the triple shot peened specimen having the same artificial corrosion pits decreased only by 14%. Therefore, it was confirmed that the triple shot peening also improves the fatigue limit of the hydrogen-charged specimens having the artificial corrosion pits. All the fatigue crack initiation sites of the double shot peened specimen were the artificial corrosion pits, as shown in Fig. 14. On the other hand, all initiation sites of the fracture of the triple shot peened specimen were fish-eye fatigue fracture surfaces with an inclusion. There is an inclusion of several tens of µm in diameter at the fatigue crack initiation site. The inclusion was located at 600–700 µm deep from the surface in the fracture surface of the triple shot peened specimen and this depth was larger than that of the artificial corrosion pits. It is considered that the fatigue fracture with inclusions is promoted by hydrogen-charging because all the fatigue crack initiation sites of the hydrogen-uncharged specimens were at the bottom of the artificial corrosion pits. This issue will be discussed in next section. It was separately confirmed that ODA was not observed around the inclusion in all hydrogen-charged and hydrogen-uncharged specimens by optical microscopy.

The fatigue limits of both the double and triple shot peened specimens having the artificial corrosion pits of
500 μm deep decreased significantly compared with the fatigue limits of the smooth specimens, as shown in Fig. 13(c). All the fatigue crack initiation sites were at the bottom of the artificial corrosion pits. Figure 16 shows the effect of shot peening on the fatigue limits of the hydrogen-charged (Fig. 13) and hydrogen-uncharged specimens (Fig. 7) as a function of the artificial corrosion pit depth. It is clearly revealed that the decrease of the fatigue limits due to deep artificial corrosion pits is improved by applying the triple shot peening instead of the double shot peening. The induction of the compressive residual stress at the relatively deeper layer is effective to improve the corrosion fatigue property even on the hydrogen-charged specimens because the deterioration rate of the fatigue limit due to hydrogen-charging is approximately 20% at most, whereas that due to the artificial corrosion pits is approximately 60–75%.

4. Discussion

4.1. Effects of Compressive Residual Stress on Fatigue Limit

The relationship between the fatigue limit and compressive residual stress at the bottom of the artificial corrosion pit is discussed. To estimate the compressive residual stress at the bottom of the artificial corrosion pit, the values of the compressive residual stress at 50, 250, and 500 μm deep were determined based on data in Fig. 5. The relationship between the compressive residual stresses and fatigue limits of the hydrogen-uncharged/hydrogen-charged specimens is shown in Figs. 17(a) and 17(b), respectively. There is a good correlation between the fatigue limits of the hydrogen-uncharged/hydrogen-charged specimens and compressive residual stress at the bottom of the artificial corrosion pits, regardless of the depth of the pits. When the stress ratio of the fatigue test ($R = \sigma_{\text{min}} / \sigma_{\text{max}}$) is minus, the compressive residual stress can be reduced when the sum of the applied and residual stresses exceeds the compressive yield stress.6,12–14) In this study, large compres-

![Fig. 16. Effect of number of shot peening on fatigue limit of hydrogen-uncharged specimens and hydrogen-charged specimens as a function of artificial corrosion pit depth. [H] stands for hydrogen-charged specimens.](image)

![Fig. 17. Relationship between fatigue limit and estimated residual stress at the origin of fracture before fatigue test. (a) hydrogen-uncharged specimen, and (b) hydrogen-charged specimen. Data of specimens without shot peening and double shot peening with 50 μm deep artificial corrosion pit are referred from previous study.](image)

![Fig. 18. Residual stress of shot peened specimens before and after fatigue test as a function of distance from surface. (a) double shot peened specimen and (b) triple shot peened specimen.](image)
sive residual stress was induced at the surface layer of the specimens by the multi-step shot peening together with the applied stress, because the stress ratio of the rotary bending fatigue test is $R = -1$. Therefore, there is a possibility that the reduction of the compressive residual stress may occur. For verifying the hypothesis, the residual stress distribution of the specimens after the fatigue test was measured. The measured residual stress after $10^7$ cycles is shown in Fig. 18, where a cyclic stress with various amplitudes was applied to the hydrogen-uncharged specimens. When the applied stress is relatively small, the reduction of the compressive residual stress is almost negligible. However, when the applied stress is relatively large, the compressive residual stress at the surface of the specimens is reduced considerably by 100–250 MPa. The residual stress distribution of the hydrogen-charged specimens was also separately measured. It was confirmed that the behavior change of the residual stress in the hydrogen-charged specimens was almost the same as that in the hydrogen-uncharged specimens. The relationship between the fatigue limit and estimated residual stress at the origin of the fracture after the fatigue test of the hydrogen-uncharged/hydrogen-charged specimens are plotted in Figs. 19(a) and 19(b), respectively. There is also a good correlation between the fatigue limits of the hydrogen-uncharged/hydrogen-charged specimens and estimated compressive residual stress at the bottom of the artificial corrosion pits when the reduction of the compressive residual stress is taken into account.

4.2 Initiation of Fatigue Crack at an Inclusion Promoted by Hydrogen-charging

All the initiation sites of the fatigue fracture of the triple shot peened specimen having the artificial corrosion pits of 250 μm deep were the fish-eye fatigue fracture with the inclusion. On the other hand, the inclusion is not the initiation site of the fatigue fracture of the hydrogen-uncharged specimens. Therefore, it is considered that the interface between the inclusion and matrix is weakened by hydrogen.

Murakami et al.\textsuperscript{11,15–17} showed that the high cycle fatigue strength is affected by the size of inclusions and hydrogen trapped around inclusions during heat treatment. Murakami and Nagata\textsuperscript{11,15–17} showed that the tension-compression fatigue limit of a high strength steel is declined remarkably by hydrogen-charging. They concluded that the reason is the effect of diffusible hydrogen, which diffuses freely in the matrix. The phenomena that a fatigue crack is accelerated by diffusible hydrogen are widely observed in various structural steels.\textsuperscript{19} It is also reported that hydrogen promotes the mobility of dislocation and propagation of a fatigue crack.\textsuperscript{20,21} On the basis of the previous studies, it is possible that diffusible hydrogen enhances dislocation mobility, resulting in the promotion of fatigue crack initiation. Murakami and Nagata\textsuperscript{18} proposed the mechanism of a fatigue crack promoted by hydrogen as described below.

(1) A crack initiates at the interface between the inclusion and matrix.
(2) The crack begins to propagate in the region around an inclusion where the trapped hydrogen content is high and thereby the threshold stress intensity factor $\Delta K_{th}$ is small.
(3) Thus, the crack easily propagates into the matrix where the diffusible hydrogen content is high. The crack does not propagate discontinuously but propagates in each cycle because it selectively propagates into the region where the diffusible hydrogen content is high and $\Delta K_{th}$ is small. Therefore, the formation of ODA becomes difficult.

In the fatigue tests of this study, it is considered that the fatigue fracture with the inclusion is promoted by the similar mechanism.

(1) A crack is initiated at the interface between the inclusion and matrix located in $>600$ μm deep, where there is no large compressive residual stress.
(2) The crack begins to propagate in the region around the inclusion where the trapped hydrogen content is high and thereby $\Delta K_{th}$ is small. On the other hand, the crack neither initiates nor progresses easily around the artificial corrosion pit because the hydrogen content around the pit is low. When a large compressive residual stress is induced at the bottom of the pit, crack propagation is prevented because crack opening becomes difficult owing to the compressive residual stress. Thus, the

![Fig. 19. Relationship between fatigue limit and estimated residual stress at the origin of fracture after fatigue test. (a) hydrogen-uncharged specimen and (b) hydrogen-charged specimen.](image-url)
crack propagates into the matrix where the diffusible hydrogen content is high, leading to the formation of a fish-eye fatigue fracture surface with the inclusion as the fatigue crack initiation site.

Considering the above-mentioned mechanism, the influence of hydrogen on the fatigue property of the suspension spring steel with the artificial corrosion pit after the multi-step shot peening is schematically illustrated in Figs. 20 and 21.

[Hydrogen-uncharged specimens (Fig. 20)]
(1) Initiation and propagation of the fatigue crack at the bottom of the pit of the double shot peened specimen are prevented when the compressive residual stress is sufficiently large at the bottom of the pit.
(2) When the pit depth exceeds the region where the large compressive residual stress exists, the fatigue limit declines significantly according to $\sqrt{\text{area}}$ (the square root of the projected area of the defect perpendicular to the direction of the maximum principal stress).\(^{22}\)
(3) When the deeper compressive residual stress layer induced by the triple shot peening exists, the initiation and propagation of the fatigue crack from the bottom of the pit can be prevented.

[Hydrogen-charged specimens (Fig. 21)]
(1) When the pit depth is shallow and thereby there is a large compressive residual stress at the bottom of the pit, the initiation and propagation of the fatigue crack from the bottom of the pit are prevented. However, the initial fatigue crack is initiated around an inclusion due to trapped hydrogen and propagates to the matrix where the diffusible hydrogen content is high, resulting in the fish-eye fracture surface frequently associated with the inclusion as the fatigue crack initiation site. In this case, the decrease of the fatigue limit due to hydrogen is smaller than that due to the pit because $\sqrt{\text{area}}$ of the inclusion is much smaller than that of the pit. Therefore, the fatigue limit decreases gently.
(2) When the pit depth exceeds than the depth of the large compressive residual stress layer, the fatigue crack initiates at the bottom of the pit, regardless of hydrogen-charging. Consequently, the fatigue limit decreases...
When the deeper compressive residual stress layer is induced by the triple shot peening, the initiation and propagation of the fatigue crack from the bottom of the deeper pit can be prevented. However, the fish-eye fracture frequently occurs due to the similar mechanism described in (1).

4.3. Effect of Stress Loading Type of Fatigue Test

The stress loading type of an automotive suspension coil spring is repetitive torsion. On the other hand, the loading type of the fatigue test in this study is rotary bending. Although the rotary bending fatigue test is a simple test to investigate the fatigue property of a material, the stress loading type of the practically serviced automotive suspension coil spring is different. Therefore, the effect of stress loading type is discussed.

Kanazawa and Abe investigated the influence of stress loading type such as rotary bending, torsional, and axle loading on the fatigue property of steels containing inclusions. They clarified that the fatigue fracture caused by the inclusion acting as the crack initiation site may occur in rotary bending and axle load fatigue tests, but no fracture caused by the inclusion acting as the crack initiation site occurs in the torsional load fatigue test. Furthermore, the fatigue limit determined by the rotary bending fatigue test is impaired by the decrease of the cleanliness of steels in terms of size and number of inclusions. However, the fatigue limit determined by the torsional fatigue test is unaffected by the cleanliness of steels. Therefore, the effect of inclusions on the fatigue limit of the torsional fatigue test is considered to be smaller than that of the rotary bending test.

The present and previous studies by the present authors clarify that the fatigue fracture that initiates at the artificial corrosion pit may occur in the specimens having the artificial corrosion pit. On the other hand, the fish-eye fatigue fracture with the inclusion as the fatigue crack initiation site frequently occurs due to diffusible hydrogen.

The good relationship between the fatigue limit after shot peening and compressive residual stress at the bottom of the artificial corrosion pit is obtained, regardless of the depth of the pit.

5. Conclusion

The effects of residual stress, artificial corrosion pit depth, and diffusible hydrogen on rotary bending fatigue properties of the specimens after the double and triple shot peening are investigated. The conclusions obtained are as follows.

(1) The fatigue limits of the specimens having the artificial corrosion pit of 250 μm deep without charged hydrogen are remarkably improved by the triple shot peening. The decrease of the fatigue limit caused by the deeper artificial corrosion pit is prevented by applying a deeper compressive residual stress. Therefore, the decrease of fatigue property can be prevented even in the case of the specimens having deep artificial corrosion pits by applying compressive residual stress at the deeper layer.

(2) The fatigue limits of the specimens having the artificial corrosion pit of 250 μm deep with charged hydrogen are also remarkably improved by the triple shot peening.

(3) The fatigue fracture initiation site of the triple shot peened specimen having the artificial corrosion pit of 250 μm deep without charged hydrogen is at the bottom of the artificial corrosion pit. On the other hand, the fish-eye fatigue fracture with the inclusion as the fatigue crack initiation site frequently occurs due to diffusible hydrogen.

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