Influence of artificial corrosion pits and hydrogen on the fatigue properties of suspension spring steel after shot peening

Manabu Kubota [a], Daisuke Hirakami [a], Takahisa Suzuki [b] and Kohsaku Ushioda [c]
[a] Steel Research Laboratories, Nippon Steel & Sumitomo Metal Corporation, Japan, kubota.7ts.manabu@jp.nssmc.com, hirakami.9fc.daisuke@jp.nssmc.com; [b] Muroran R&D Lab. Nippon Steel & Sumitomo Metal Corporation, Japan, suzuki.9xg.takahisa@jp.nssmc.com; [c] R&D Laboratories, Nippon Steel & Sumitomo Metal Corporation, Japan, ushioda.cd8.kohsaku@jp.nssmc.com

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Introduction

To reduce the weight of automotive suspension springs, increasing the strength level of the spring steel is effective because the fatigue strength of the spring steel increases with the strength of the spring steel. However, it is considered that the corrosion fatigue phenomenon becomes pronounced with an increase in the strength level of the spring steel. Therefore, to increase the strength of suspension springs, improvement in the corrosion fatigue properties is one of the most important issues.

Fatigue cracks in actual suspension springs initiate at the corrosion pit [1,2]. The actual corrosion pits of automotive suspension coil springs have been investigated in [1], wherein the average value of the maximum corrosion pit depth of all the investigated coil springs was approximately 150 μm and the maximum corrosion pit depth was 250 μm. These values are approximately equal to the depth of the compressive residual stress layer that is formed under typical shot peening conditions. Therefore, it is considered that the fatigue strength of suspension springs decreases because of the presence of corrosion pits. It has been demonstrated that compressive residual stress makes shallow artificial corrosion pits harmless [3,4].

In addition, since hydrogen is generated on the surface of steel because of the corrosion reaction, the effect of hydrogen on the corrosion fatigue properties should also be considered because hydrogen promotes the initiation and propagation of fatigue cracks [5-7].

Objectives

Thus far, only a few studies have satisfactorily investigated the relationship between compressive residual stress and the corrosion fatigue properties of suspension springs. In this study, the effects of diffusible hydrogen and the artificial corrosion pit depth on the fatigue properties of suspension spring steel after multi-step shot peening were investigated.

Methodology

SAE9254 (Fe–0.55C–1.5Si–0.7Mn–0.7Cr (mass%)), a typical steel grade for suspension springs, was used. Steel was hot-rolled wire rod with 13 mm in diameter. Then, it was quenched and tempered in a laboratory to obtain tempered martensite microstructure. The condition of heat treatment and mechanical properties of the specimens are shown in Table 1. Specimens for a rotary bending fatigue test were prepared via machining. The length of the parallel portion of the specimens was 10 mm with 8 mm in diameter or 15 mm with 6 mm in diameter. Then, the parallel and round portions of the specimens were polished along the longitudinal direction using emery paper. The preparation procedure of the specimens is shown in Fig. 1

Table 1 Heat-treatment condition and mechanical properties of material investigated.

Austenitizing	Tempering	0.2% proof stress (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)
950°C×0.9ks	425°C×1.8ks	1625	1807	11.4	36.5

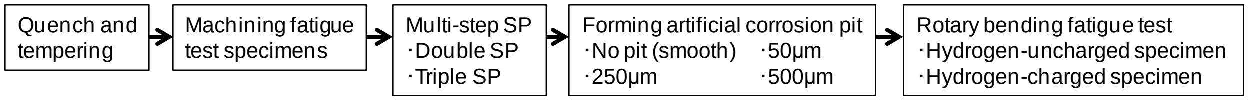

Fig. 1 Preparation procedure for the fatigue test specimens.

Multistep shot peening was performed under various conditions using an impeller-type shot peening machine. The conditions for this process, shown in Table 2, included conventional double shot peening and triple shot peening, which was newly applied in this study. The residual stress at the center of the parallel portion of the specimens was measured using a microarea X-ray residual stress measurement system (AutoMate, Rigaku Corp.). The measurement direction of the residual stress was the longitudinal direction of the specimens. The residual stress distributions were measured as functions of depth by polishing the specimens electrically.

Table 2 Multi-step shot peening conditions for the fatigue specimens. SP stands for shot peening.

Materials of shot peening		Condition of shot peening			Specimen	
Diameter (mm)	Hardness (HV)	Velocity (m/s)	Rotating speed (rpm)	Time (s)	Double SP	Triple SP
1.7	560			40		1st SP
0.8	600	73	23	14	1st SP	2nd SP
0.2	700			10	2nd SP	3rd SP

Artificial corrosion pit depths of 50, 250 and 500 μm were used. Artificial corrosion pits were produced in some of the fatigue specimens using electric discharge machining. The number of the artificial corrosion pits was one per fatigue specimen, and the pit was located at the center of the parallel portion of the specimen. The artificial corrosion pits were cylindrical holes with 1 mm in diameter. A schematic of the pits is shown in Fig. 2.

A rotary bending fatigue test was conducted. In the test, the rotation speed was 2000 rpm and the maximum number of cycles was 10^7. Hydrogen charging and zinc plating were applied to some of the fatigue specimens to prevent hydrogen discharging. The procedure of the fatigue test after hydrogen charging is shown in Fig. 3. The diffusible hydrogen content in the specimen was measured via thermal desorption spectrometry (TDS) using a gas chromatograph. The heating rate was 100°C/h. Diffusible hydrogen was defined as the hydrogen discharged between the room temperature and 200°C.

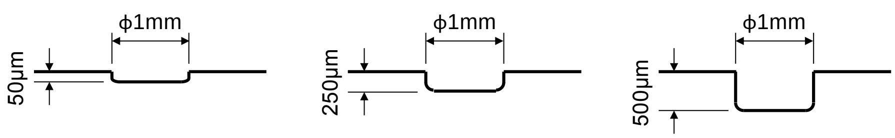

Fig. 2 Schematic illustration of artificial corrosion pits.

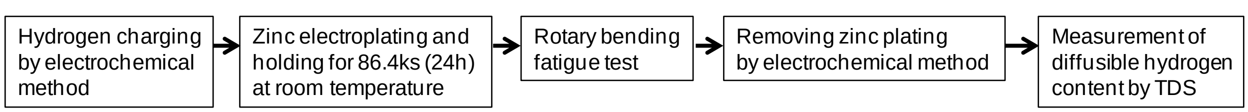

Fig. 3 Experimental procedure for the fatigue test with hydrogen charging. TDS stands for thermal desorption spectrometry.

Results and analysis

The residual stress distributions in the specimens are shown in Fig. 4. The residual stresses at the surface and the maximum residual stresses in the double and the triple shot peened specimens were almost the same. The layer containing a large compressive residual stress in the triple shot peened specimen was much deeper than that in the double shot peened specimen.

The effects of multistep shot peening on the fatigue limit as a function of the artificial corrosion pit depth are shown in Fig. 5 [8]. The fatigue limit of the specimen without shot peening and containing an artificial corrosion pit 50 μm deep remarkably decreased (by 61%) in comparison to that of the smooth specimen. In contrast, the fatigue limit of the double shot peened specimen containing the same artificial corrosion pit decreased by only 7%. Thus, the reduction in the fatigue limit due to the 50 μm deep artificial corrosion pit was prevented by double shot peening. The fatigue limit of the double shot peened specimen containing a 250 μm deep artificial corrosion pit decreased by 57%. In contrast, the fatigue limit of the triple shot peened specimen having the same artificial corrosion pit decreased by only 14%. Thus, the reduction in the fatigue limit due to the deeper artificial corrosion pit was prevented by triple shot peening. The fatigue limits of the specimens having 500 μm deep artificial corrosion pits significantly decreased regardless of multistep shot peening. This indicates that there is a certain relationship between the fatigue limit, artificial corrosion pit depth, and type of multistep shot peening.

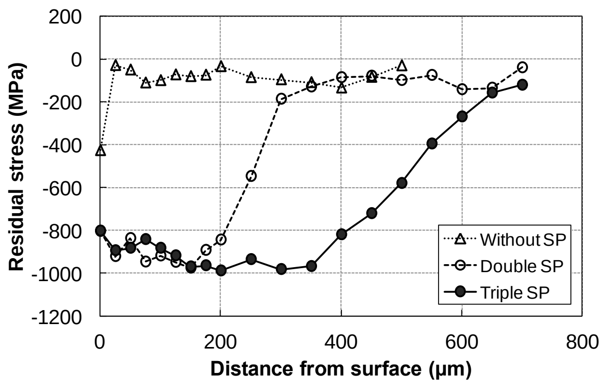

Fig. 4 Residual stress distributions in the fatigue specimens.

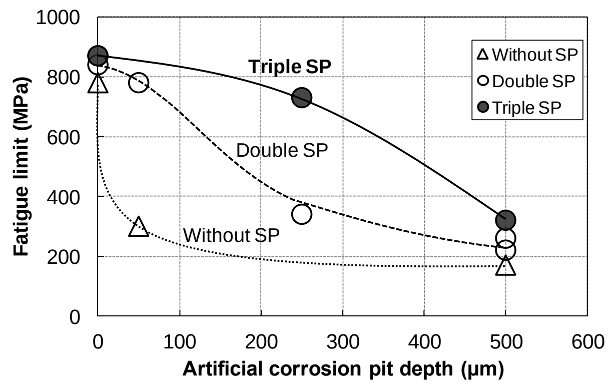

Fig. 5 Effect of multistep shot peening on fatigue limit as a function of artificial corrosion pit depth.

The fatigue crack initiation site in the smooth specimen without shot peening was at the surface. Several fish-eye fracture surfaces of the double and the triple shot peened smooth specimens were observed nearby an inclusion as the fatigue crack initiation sites. The diameter of the inclusions was of the order of several tens of μm, and they were located at depths of 300 μm and 560–930 μm from the surface of the double and the triple shot peened specimens, respectively. These results indicate that the initiation of the fatigue crack at the surface was prevented because of the large compressive residual stress. Consequently, the inclusions located in the deeper layer, where a large compressive residual stress does not exist, became the fatigue crack initiation sites for the multistep shot peened smooth specimens. Conversely, the fatigue crack initiation sites of all the specimens having the various artificial corrosion pits depth were at the bottom of the pits.

To discuss the relationship between the fatigue limit and compressive residual stress at the bottom of artificial corrosion pits, the values of the residual stress at depths of 50, 250 and 500 μm were determined based on the data shown in Fig. 4 as the estimated values of the residual stress at the bottom of the pits. The relationship between the compressive residual stress and fatigue limits of the specimens having artificial corrosion pits is shown in Fig. 6 [8]. It can be seen that there is a good correlation between the compressive residual stress and fatigue limit regardless of the depth of the artificial corrosion pits and the conditions for multistep shot peening. Therefore, it is effective to introduce a larger compressive residual stress at a deeper layer for improving the fatigue property of spring steel having deep corrosion pits.

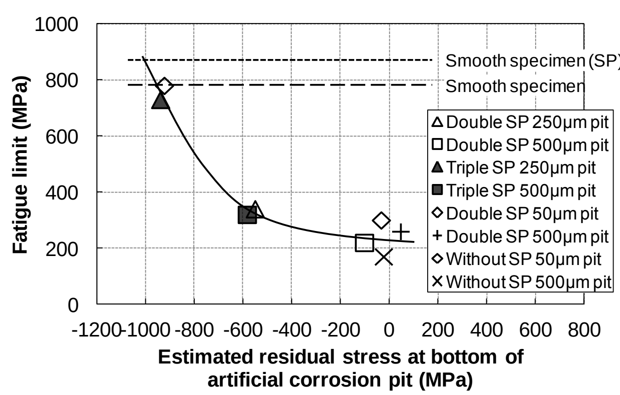

Fig. 6 Relationship between fatigue limit and estimated residual stress at the bottom of the artificial corrosion pit.

The effects of the diffusible hydrogen content and double shot peening on the fatigue limit of the smooth specimens and that of the specimens having artificial corrosion pits 50–500 μm deep are shown in Fig. 7 [9]. The fatigue limits of the smooth specimens gradually decreased by approximately only 30% with an increase in the diffusible hydrogen content with or without the shot peening, as shown in Fig. 7(a). The fatigue limit of the double shot peened specimen having a 50 μm deep artificial corrosion pit also gradually decreased by only 23% with an increase in the diffusible hydrogen content, as shown in Fig. 7(b). In contrast, the fatigue limit of the specimen without shot peening significantly decreased by 62% owing to the artificial corrosion pit even when diffusible hydrogen was not charged. This means that the reduction in the fatigue limit due to the 50 μm deep artificial corrosion pit was prevented by double shot peening even when diffusible hydrogen existed in the steel. The fatigue limits of all the specimens having 500 μm deep artificial corrosion pits significantly decreased owing to the deep artificial corrosion pits, as shown in Fig. 7(c). The effects of double shot peening and diffusible hydrogen on the fatigue limit were almost negligible.

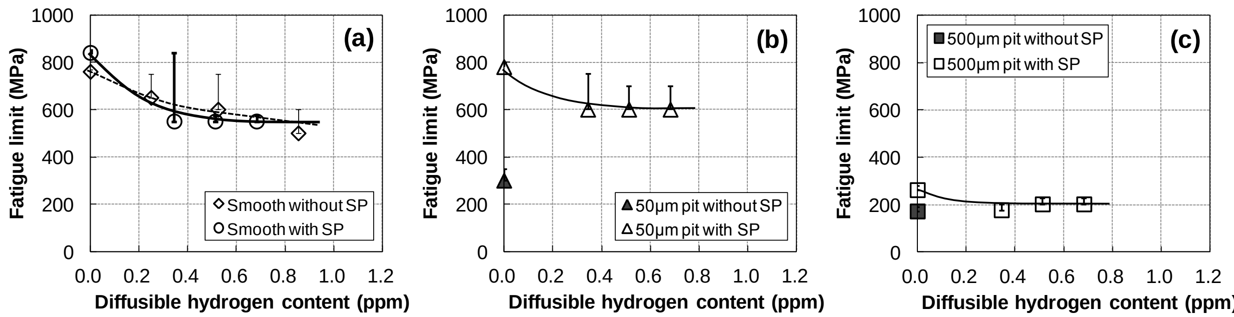

Fig. 7 Relationship between diffusible hydrogen content and the fatigue limit of double shot peened specimens. (a) Smooth specimen, (b) specimen having a 50μm deep artificial corrosion pit, and (c) specimen having a 500μm deep artificial corrosion pit.

The effect of multistep shot peening on the fatigue limits of the hydrogen-charged and hydrogen-uncharged specimens as a function of artificial corrosion pit depth is shown in Fig. 8. The diffusible hydrogen content in the hydrogen-charged specimens was 0.6–0.9 ppm. The fatigue limits decreased by approximately 20%–30%; however, the fatigue limits of the specimens having 250 μm deep artificial corrosion pits with and without hydrogen charging were remarkably improved by triple shot peening. It was concluded that the introduction of a larger compressive residual stress at a deeper layer is effective for improving the fatigue property of spring steel having deep corrosion pits even when diffusible hydrogen exists in the steel. The fatigue crack initiation sites of the triple shot peened specimens having 250 μm deep artificial corrosion pits were at the bottom

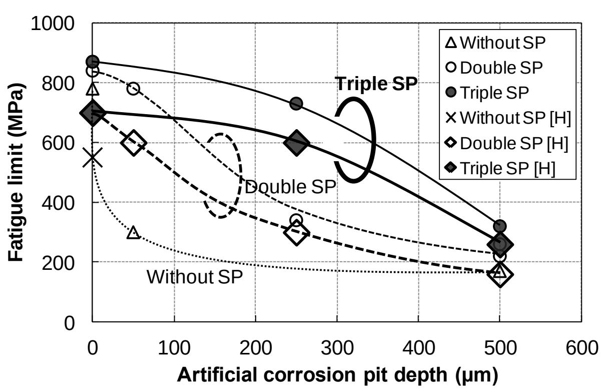

Fig. 8 Effect of multi-step shot peening on fatigue limit of hydrogen uncharged specimens and hydrogen charged specimens as a function of artificial corrosion pit depth.

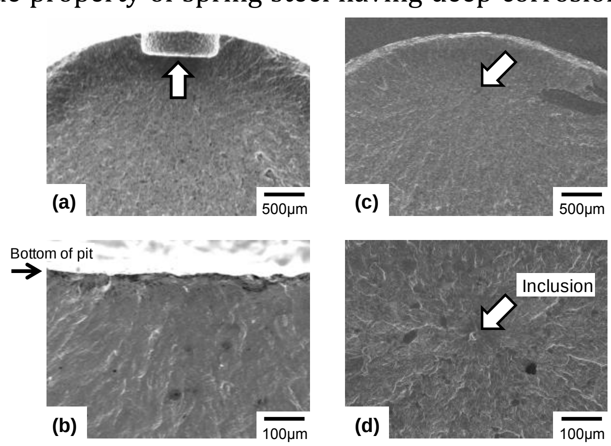

Fig. 9 Typical fracture surfaces of triple shot peened specimens having 250μm deep artificial corrosion pits. (a) Hydrogen-uncharged specimen, (b) highly magnified image showing the bottom of an artificial corrosion pit as the fatigue crack initiation site, (c) hydrogen-charged specimen, and (d) highly magnified image showing an inclusion as the fatigue crack initiation site.

of the pits when hydrogen was not charged, as shown in Fig. 9(a). On the other hand, all the fatigue crack initiation sites of the triple shot peened specimens having 250 μm deep artificial corrosion pits were nearby an inclusion when the hydrogen was charged, as shown in Fig. 9(b) [8]. The inclusion was located at a depth of 600–700 μm from the surface of the specimen, where large compressive residual stress does not exist. Therefore, it seems that the interface between the inclusion and the matrix or the matrix around the inclusion was weakened by diffusible hydrogen. It is likely that the initial fatigue crack was initiated around an inclusion because of the hydrogen trapped around it and propagated to the matrix where the diffusible hydrogen content was high [10], thereby resulting in the fish-eye fatigue.

Conclusions

(1) The fatigue limits of the specimens having artificial corrosion pits were remarkably improved by the introduction of a larger compressive residual stress at a deeper layer.
(2) There is a good correlation between the fatigue limits of the specimen having artificial corrosion pits and the compressive residual stress at the bottom of the pits.
(3) The fatigue limits gradually decreased with increasing diffusible hydrogen content.
(4) The fatigue limits remarkably decreased when the artificial corrosion pit was deeper than the layer having a large compressive residual stress. On the other hand, the reduction in fatigue limits due to diffusible hydrogen was relatively small.
(5) Introduction of a larger compressive residual stress at a deeper layer is effective for improving the fatigue property of spring steel having deep corrosion pits even when diffusible hydrogen exists in the steel.

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