IMPROVEMENT OF BENDING FATIGUE LIMIT BY SHOT PEENING FOR SPRING STEEL SPECIMENS CONTAINING AN ARTIFICIAL SURFACE DEFECT

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ABSTRACT

Effects of shot peening on the bending fatigue limit of spring steel specimens (SUP9A) containing an artificial small hole were investigated. Shot peening (SP) and stress shot peening (SSP) were carried out with specimens containing an artificial drilled hole 0.2, 0.4 and 0.8 mm in diameter. Bending fatigue tests were carried out with the specimens. The fatigue limits of specimens containing an artificial small hole were increased by shot peening. Stress shot peening (SSP) was more effective in improving fatigue limit. The specimens containing an artificial hole of a 0.2 mm diameter which received SP or SSP fractured elsewhere than on the hole, and they had very high fatigue limits. The fatigue limit of specimens having an artificial hole under 0.2mm in diameter was determined by threshold condition for the non-propagation of fatigue cracks that emanated outside the drilled hole. From these results, it can be concluded that an artificial drilled hole under 0.2 mm in diameter can be made non-damaging by shot peening.

KEY WORDS

Shot peening, Bending, Fatigue limit, Surface defect, Residual stress, Non-propagating crack

INTRODUCTION

Requirements to improve the fatigue limit of vehicle components are increasing year by year from the viewpoint of environmental and energy conservation issues. There are mainly two popular ways to increase fatigue limit: (a) increase the hardness of materials, and (b) introduce compressive residual stress in components. However, for technique (a), because the Vickers hardness (*HV*) of currently-used vehicle components such as springs and gears is very high, approximately 600*HV*, it is difficult to increase the hardness further. Moreover, if the *HV* is increased further, the materials will be too sensitive for corrosion fatigue and hydrogen embitterment. For technique (b), shot peening is a very popular technique for inducing compressive residual stress (S. Suresh, 1991). Shot peening is especially useful for components that are subjected to a cyclic load with a stress ratio $R \geqq 0$. For this reason, in order to improve fatigue limit, shot peening has been widely used, and its various techniques have been developed (H. Ishigami, 2000; L. Wagner, 2002).
Fatigue fractures of components are often caused by surface defects because the maximum stress occurs on the surfaces in components such as springs and gears. Many studies have been carried out to investigate the effects of surface defects on fatigue limit (Y. Murakami, 2002). There is a critical size for defects which does not

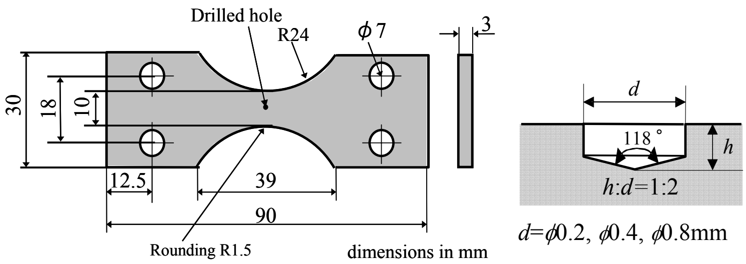
lower the fatigue limit. The critical size is smaller for materials having a higher fatigue limit. If the critical defect size can be increased by SP, the reliability could be increased and manufacturing cost could be decreased. However, there are few studies regarding the effects of shot peening on materials containing an original surface defect (M. Kuwahara, 2004). In this study, in order to find and propose a method to improve fatigue limit and to make the surface defect non-damaging, we conducted shot peening on spring steel specimens containing an artificial small hole, and we carried out a plane-bending fatigue test using the specimens.

EXPERIMENTAL PROCEDURES

The spring steel used in the present study was Japanese Industrial Standards (JIS) SUP9. Table 1 shows its chemical composition (mass %). Fig. 1 shows the shape and dimension of a specimen and a small hole. The specimens used in the present study were non-defect specimens and specimens containing an artificially-drilled hole, with the ratio of diameter (*d*) to depth (*h*) being $h=1/2d$, as shown in Fig. 1 (b). The diameters of the drilled holes were 0.2mm, 0.4mm and 0.8mm, respectively. After the machining of a specimen, a drilled hole was introduced at its center. Then, the specimens were oil-quenched at 860 °C and tempered at 300°C. The Vickers hardness of the specimens after heat treatment was 570*HV*.

Table 1 Chemical composition of SUP9(mass %).

Material	C	Si	Mn	P	S	Cu	Ni	Cr
SUP9	0.57	0.25	0.86	0.022	0.019	0.2	0.11	0.82



(a) Plane-bending specimen. (b) Drillied hole.

Fig.1 Shape and dimension of specimen and hole.

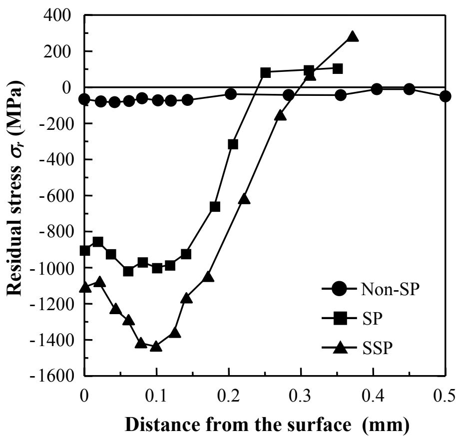


Fig.2 Residual stress distribution.

After heat treatment, the authors conducted shot peening on non-defect specimens and specimens with a small hole. Table 2 shows the shot-peening conditions adopted in this study. The shot peening was carried out with a direct pressure peening system. The shot used was conditioned cut wire of steel with a diameter of 0.67mm and a hardness of 600*HV*.

In this study, stress shot peening was also carried out. A four-point bending system was used to apply stress. The stress on the surface was measured using a strain gage. The tensile stress applied to the specimens was 1250 MPa. In this study, normal shot peening without stresses is called SP, and stress shot peening is called SSP.

The residual stress distributions induced by SP and SSP are shown in Fig. 2, where σ_s, σ_{max} and d_0 are the compressive residual stress on the surface, the maximum compressive residual stress and the distance from the surface to the zero residual

stress point (crossing point), respectively. The σ_{max} and the σ_s were remarkably increased by SSP.
Table 3 shows surface roughness before and after SP and SSP. The value of surface roughness increased after both. However, these values of surface roughness were much smaller than the depth of the artificial drilled hole (0.1 – 0.4 mm). It was revealed from measurements that there was no change in hardness after shot peening and that the hardness did not change from the surface to the center of the specimen.
Fatigue tests were carried out on the above specimens. The plane-bending fatigue testing machine was used. The fatigue test conditions were a stress ratio of R=0 and a cyclic frequency of 20 Hz. The stress wave form was a sine wave. The fatigue limit was defined as the maximum stress amplitude under which the specimen endured 10^7 cycles.

Table 2 Shot peening condition.

Peening machine	Direct pressure peening
Air pressure	0.62MPa
Shot diameter	0.67mm
Shot hardness	600HV
Shot time (one side)	40 s
Shot distance	100mm
Coverage	300%
Arc height	0.496mmA

Table 3 Surface roughness (μm).

	Non-SP	SP	SSP
Ra	0.2	1.2	1.3
Ry	1.5	5.4	6.3

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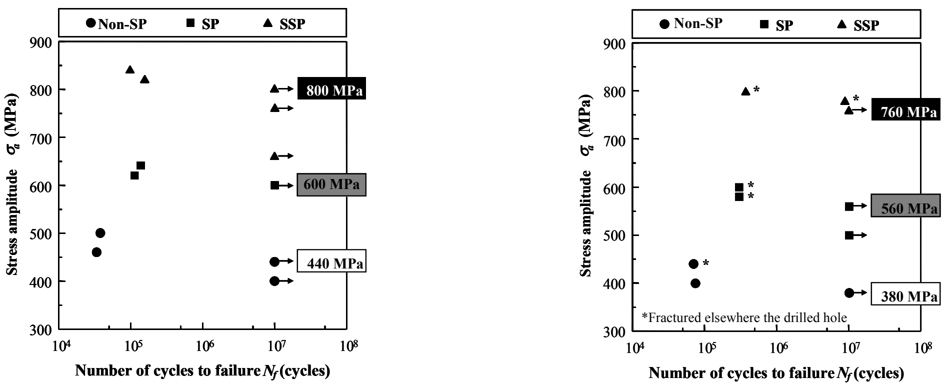
EXPERIMENTAL RESULTS AND DISCUSSIONS

Effects of shot peening on bending fatigue limit

Figs. 3(a) and 3(b) show the relationship between the stress amplitude (σ_a) and the number of cycles to failure (N_f) for non-defect specimens and specimens with a 0.2 mm hole. The symbol ● indicates a non-shot-peened specimen (Non-SP). The symbols ■ and ▲ indicate shot-peened (SP) and stress shot-peened (SSP) specimens, respectively. The asterisk symbols indicate that the specimen fractured elsewhere than on the drilled hole. The arrow indicates that the fracture had not occurred when the test was terminated at 10^7 cycles. The values of the fatigue limit are indicated in Figs. 3(a) and 3(b). By shot peening, the fatigue limit and the fatigue life of the specimens dramatically increased.



(a)Smooth specimen (b) $d = \phi0.2$mm

Fig.3 *S-N* curve for plane bending fatigue test (SUP9A, 570*HV*, *R*=0).

Size of drilled hole which can be made non-damaging by shot peening

Fig. 4 shows the results of the plane-bending fatigue tests, which show the relationship between the stress amplitude and the diameter of holes. The solid symbols represent the specimens fractured during fatigue tests. The open symbols represent the specimens which did not fracture at up to 10^7 cycles, where the maximum stress amplitude corresponds to the fatigue limit. The asterisk symbols indicate that the specimen fractured elsewhere than on the drilled hole.

The dashed lines in Fig. 4 represent the fatigue limit. The fatigue limit increased 22%-51% for SP specimens and 72%-100% for SSP specimens compared with Non-SP specimens. To increase the fatigue limit of specimens containing surface defects, it is effective to make the values of σ_s and σ_{max} large. In 0.2mm-holed-SP and 0.2mm-holed-SSP specimens, all specimens fractured elsewhere than on the drilled hole. Therefore, the fatigue limits of 0.2mm-holed-SP and 0.2mm-holed-SSP specimens are equivalent to those of non-defect-SP and non-defect-SSP specimens, respectively. In 0.4 mm-holed-SP and 0.4 mm-holed-SSP specimens, although strength reduction rates in contrast to non-defect-SP and non-defect-SSP specimens are small, all specimens fractured from the drilled hole. Therefore, it was found that drilled holes under 0.2mm in diameter could be made non-damaging by SP and SSP.

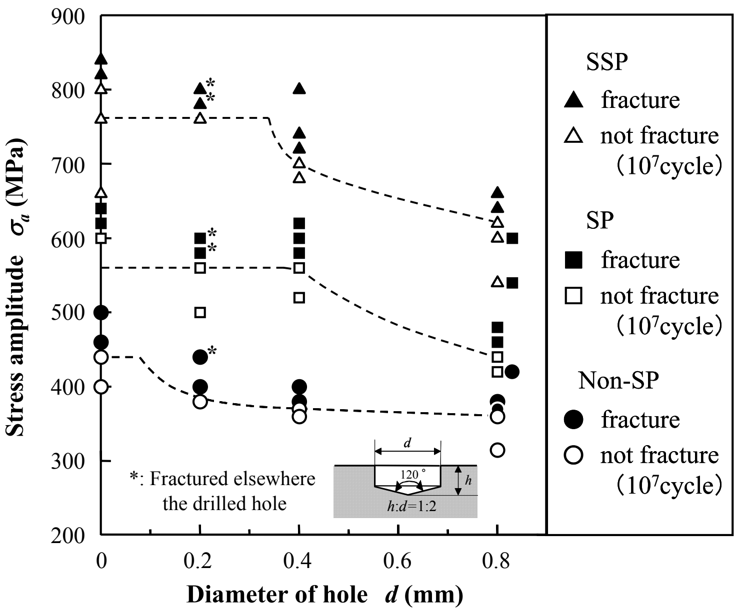


Fig.4 Relationship between stress amplitude and diameter of hole.

Observation of fatigue fracture surface

Fig. 5 shows SEM images of fractured surfaces for specimens having drilled holes with diameters of 0.2 mm, 0.4 mm and 0.8 mm. As already mentioned, SP and SSP specimens having a 0.2 mm hole fractured elsewhere than on the drilled hole. As a result, we found that a small hole with a diameter of 0.2 mm or less could be made non-damaging by shot peening. On the other hands, SP and SSP specimens having a 0.4 mm or 0.8 mm hole fractured from the drilled hole.

The small holes were deformed by SP and SSP. The fatigue limit of the materials with surface defects was increased mainly by shot peening because of compressive residual stress. Deforming the surface defects also contributed to increasing the fatigue limit and making the defect size small.

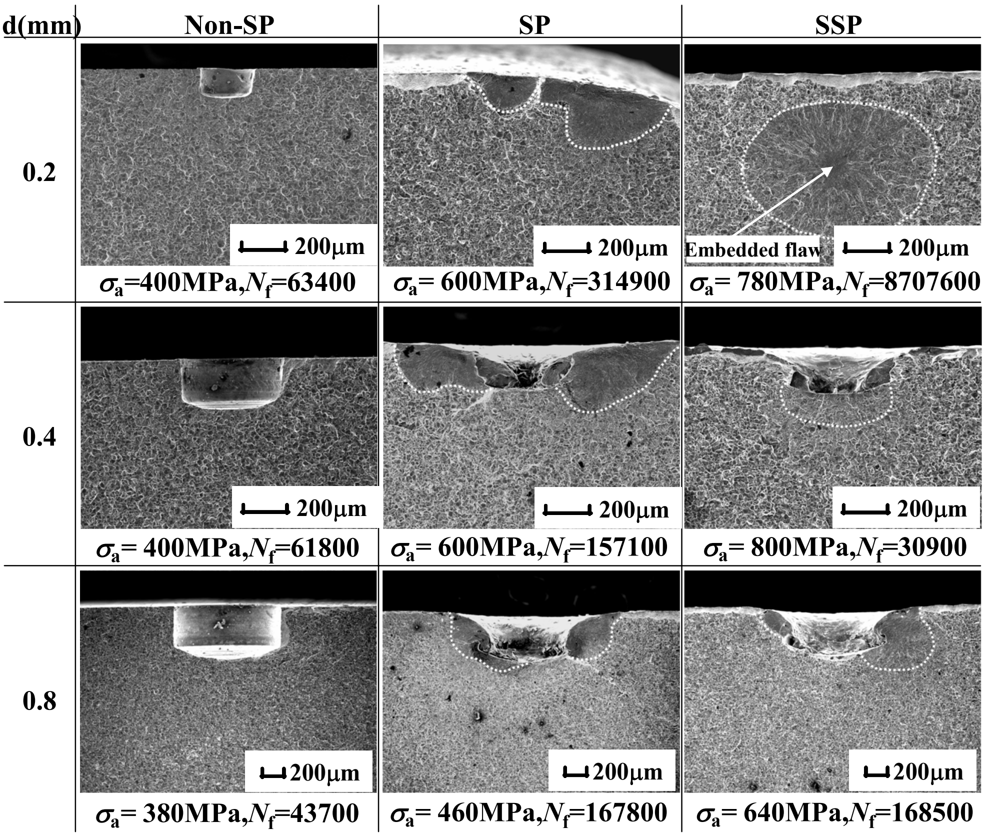


Fig.5 Fatigue fracture surface.

Non-propagating cracks

Defects smaller than a critical size are non-damaging to the fatigue limit of metals, and the critical size is smaller for metals having a higher static strength. The size of non-propagating cracks is related to the critical defect size. In this study, it was found that a drilled hole of 0.2mm or less in diameter was made non-damaging by SP and SSP. In order to find this reason, it is essential to investigate the size of non-propagating cracks. It is difficult to determine a non-propagating crack size by surface observation due to the surface roughness after shot peening. Thus, the specimens tested under the fatigue limit were heat-treated at 280 ^oC in air to produce a heat tint color. Then, they were compulsory-fractured after cooling with liquid nitrogen.

Several non-propagating cracks were observed on the fracture surfaces of specimens. All non-propagating cracks emanated from the smooth part rather than the drilled hole in 0.2 mm-holed SP or 0.2 mm-holed SSP specimens. Fig. 6 shows the fracture surface of a 0.2mm-holed SSP specimen. Non-propagating cracks approximately 0.1 mm in maximum depth existed without causing a specimen fracture. This reason is that compressive residual stress decreases the stress intensity factors at the crack tip. A drilled hole with a diameter of 0.2mm was made non-damaging by shot peening because it was smaller than the size of the non-propagating crack.

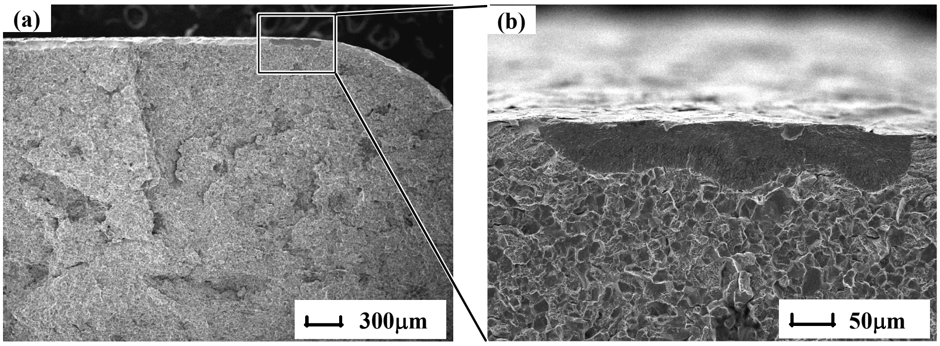


Fig.6 Non-propagating crack observed on the fracture surface of specimen tested under fatigue limit (d=ϕ0.2mm, SSP, σ_a=760MPa). (a) shows lower magnification of compulsory fractured surface after heat tint and (b) shows higher magnification .

CONCLUSION

(1) The fatigue limit of spring steel specimens containing a surface defect increased by shot peening. The fatigue limits increased 22%-51% for shot-peened (SP) specimens and 72%-100% increased for stress shot-peened (SSP) specimens in contrast to non-shot-peened (Non-SP) specimens.
(2) The specimens with a 0.2mm drilled hole subjected to SP or SSP became fractured elsewhere than on the drilled hole and had very high fatigue limits almost equal to those of the non-defect shot-peened specimens. For this reason, an artificial drilled hole under 0.2 mm in diameter can be made non-damaging by SP or SSP.
(3) The fatigue limit of the specimens with a drilled hole with a diameter under 0.2mm subjected to SP or SSP was determined to show the condition for the non-propagation of fatigue cracks emanating elsewhere than on the drilled hole. This is a reason that a drilled hole with a diameter under 0.2mm was made non-damaging by shot peening.
(4) The fatigue limit of materials with surface defects was increased by shot peening because of compressive residual stress. Deforming the surface defects also contributed to increasing the fatigue limit because stress concentration factors at the edge of holes decreased by the deformation.

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