EFFECTS OF SHOT PEENING ON TORSIONAL FATIGUE LIMIT FOR SPRING STEEL SPECIMENS CONTANING AN ARTIFICIAL SURFACE DEFECT

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ABSTRACT
Effects of shot peening on the torsional fatigue limit of spring steel specimens containing an artificial small hole were investigated. A drilled hole of 0.2 – 0.8 mm in diameter or a semi-circular slit with diameter of 0.3 and 0.6 mm was introduced on the specimen surface. Then, torsional fatigue tests were carried out with the specimens. The torsional fatigue limits of specimens containing a drilled hole or a semi-circular slit were increased by SP 25 – 64 % or 156 – 186 %, respectively. The specimens containing a drilled hole under 0.3 mm in diameter and a semi-circular slit under 0.3 mm in diameter had very high fatigue limits almost equal to those of non-defect shot-peened specimens. From these results, it can be concluded that a drilled hole under 0.3 mm in diameter and a semi-circular slit under 0.3 mm in diameter can be made non-damaging by SP.

KEY WORDS
Shot peening, Torsional fatigue limit, Surface defect, Residual stress

INTRODUCTION

The fatigue strengths of steels used for vehicle components are increasing year by year from the energy and environment conservation point of view. As the hardness of materials increased, defect sensitivity of materials tends to increase. Therefore, achieving a good balance between high fatigue strength and reliability is a significant challenge. Shot peening is especially useful for components that are subjected to a cyclic load with a stress ratio $R \geqq 0$ (H. Ishigami, 2000). 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; K. Tange, 2002).
Vehicle components, such as coil springs, crank shafts and drive shafts are subjected to cyclic torsion. Fatigue failure of these components is often caused by surface defects because the maximum stress occurs on the surfaces under torsional loading. The effects of artificial small defects on torsional fatigue strength have been studied in various materials using specimens which contain a small drilled hole (M. Endo, 1987) or a pre-crack (Y. Murakami, 1998). There is a critical size for defects which does not lower the fatigue limit. If the critical defect size could be increased by SP, the reliability could be increased and manufacturing cost could be decreased.

There are few studies regarding the effects of shot peening on materials containing an original surface defect (M. Kuwahara, 2004; K. Takahashi, 2007). Takahashi *et al.* showed that bending fatigue limit of spring steel specimens containing a small drilled hole could be increased by shot peening and small hole with diameter under 0.3 mm could be non-damaging from the viewpoint of fatigue limit. However, the effects of shot peening on the torsional fatigue limit of spring steel specimens containing a surface defect have not been studied.

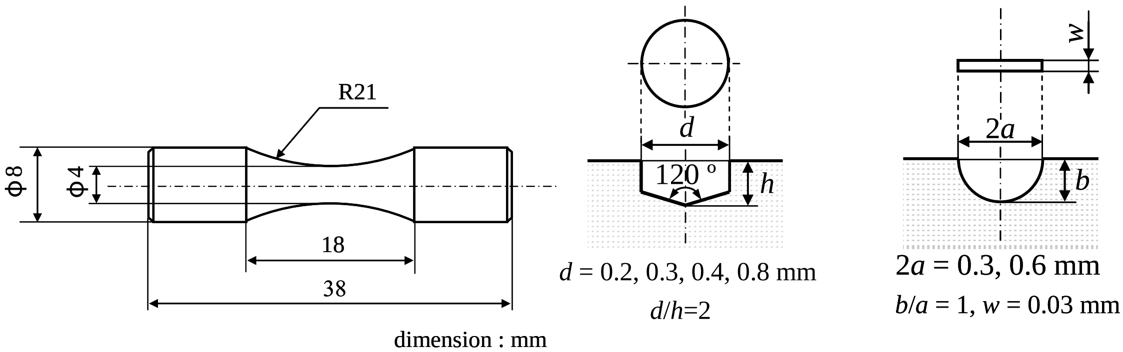
In this study, in order to investigate the effects of shot peening on torsional fatigue limit spring steel specimens containing an artificial surface defect, we conducted shot peening on spring steel specimens containing a drilled hole or a semi-circular slit, and we carried out a torsional fatigue test 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 (wt.%). Fig. 1(a) shows the shape and dimension of a torsional fatigue test specimen. In the present study, non-defect specimens, specimens with an artificially-drilled hole and semi-circular slit were used. Fig. 1 (b) shows the shape of drilled hole. The ratio of diameter (d) to depth (h) of drilled hole is h=1/2d. The diameters of the drilled holes were 0.2mm, 0.3mm, 0.4mm and 0.8mm, respectively. Fig. 1(c) shows the shape of semi-circular slit. The semi-circular slit simulates a crack like defect. The surface lengths of the semi-circular slit were 0.3 mm and 0.6 mm. The semi-circular slit was introduced by electric discharging. After the machining of a specimen, a drilled hole or a semi-circular slit was introduced at its center. Next, the specimens were oil-quenched at 860 ^{o}C and tempered at 420 ^{o}C. The Vickers hardness of the specimens after heat treatment was 520*HV*.

Table 1 Chemical composition of SUP9(wt%).

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) Test specimen (b) Drilled hole (c) Semi-circular slit

Fig.1 Shape and dimension of torsional fatigue test specimen and artificial defects.

After heat treatment, shot peening was performed on non-defect specimens and specimens with an artificial surface defect. 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*.

The residual stress distributions induced by SP are shown in Fig. 2, where σ_s, σ_{max} and d_0 are the compressive residual stress at 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 in axial direction induced by the SP were about 780 MPa and 680 MPa, respectively. The d_0 was 0.29 mm.
Table 3 shows surface roughness before and after SP. 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) and semi-circular slit (0.15 and 0.3 mm). It was revealed from measurements that there was no change in hardness after shot peening and that the hardness did not change remarkably from the surface to the center of the specimen as shown in Fig.3.
Torsional fatigue tests were carried out on the above specimens. The torsional 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
Nozzle diameter	5mm
Shot time (one side)	40s
Shot distance	100mm
Coverage	300%
Arc height	0.50mmA

Table 3 Surface roughness (μm).

	Ra [μm]	Ry [μm]
Non SP	0.54	3.96
SP	1.92	9.57

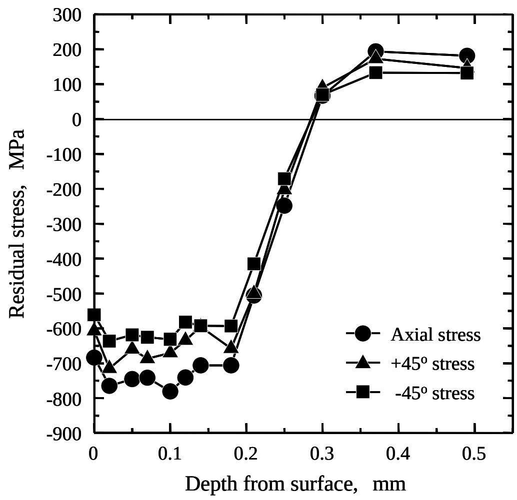


Fig. 2 Distribution of residual stress in torsional fatigue test specimen.

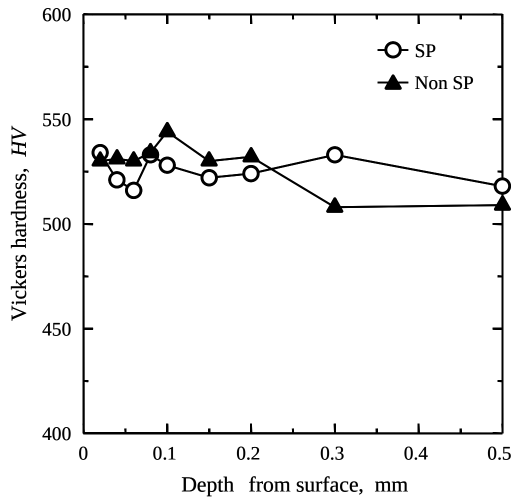


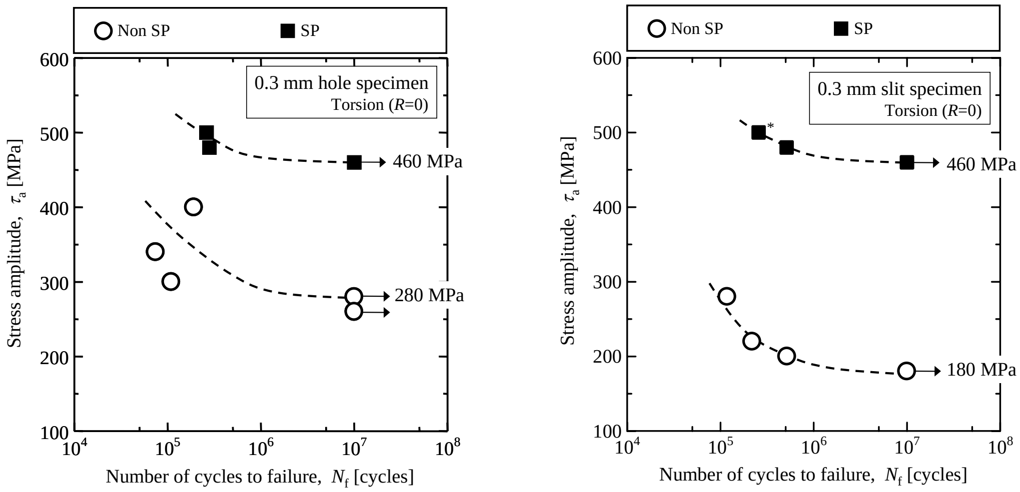
Fig. 3 Distribution of Vickers hardness in torsional fatigue test specimen.

EXPERIMENTAL RESULTS AND DISCUSSIONS

S-N diagram

Figs. 4(a) and (b) show the relationship between the stress amplitude (τ_a) and the number of cycles to failure (N_f) for specimens with drilled hole (d=0.3mm) and specimens with semi-circular slit (2c=0.3mm), respectively. The symbol ○ indicates a non-shot-peened specimen (Non-SP). The symbols ■ indicate shot-peened specimens(SP). The asterisk symbols indicate that the specimen failed elsewhere than on the drilled hole. The arrow indicates that the failure had not occurred when the test was terminated at 10^7 cycles. The values of the fatigue limit are indicated in

Figs. 4(a) and (b). By shot peening, the torsional fatigue limit and the fatigue life of the specimens increased.



(a) d=ϕ0.3 mm hole (c) 2a=0.3 mm slit

Fig. 4 S-N curves for torsinal fatigue test (SUP9A, 520HV, R=0).

Effects of shot peening on torsional fatigue limit of specimens having a drilled hole

Fig. 5 shows the results of the torsional fatigue tests for specimens having a drilled hole, which show the relationship between the stress amplitude and the diameter of holes. The solid symbols represent the specimens failed during fatigue tests. The open symbols represent the specimens which did not fail at up to 10^7 cycles, where the maximum stress amplitude corresponds to the fatigue limit. The asterisk symbols indicate that the specimen failed elsewhere than on the drilled hole. The dashed lines in Fig. 5 represent the fatigue limit. It was found that the torsional fatigue limit of specimens having drilled hole could be increased 25 % - 64 % by SP. It is known that there is a critical diameter of hole which does not decrease torsional fatigue limit. Thus, the torsional fatigue limit is shown by bending of dash line at presumed critical diameter.

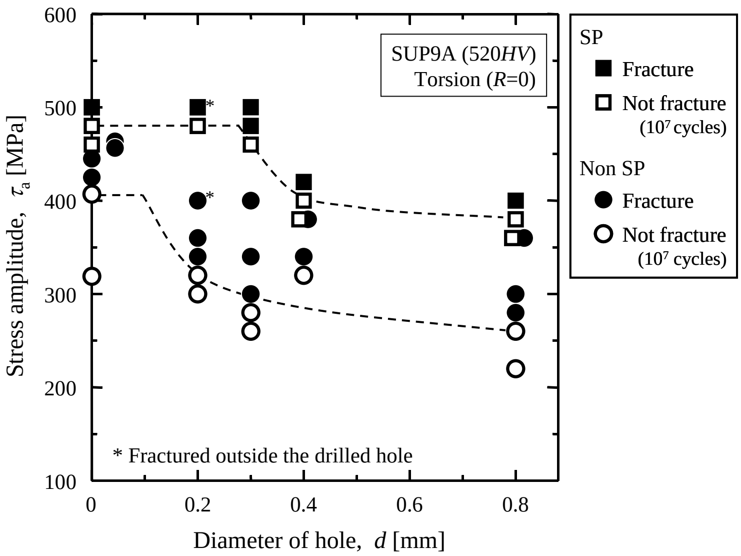


Fig.5 Relationship between stress amplitude and diameter of hole (SUP9A, 520HV, torsion, R=0).

Effects of shot peening on torsional fatigue limit of specimens having a semi-circular slit

Fig. 6 shows the results of the torsional fatigue tests for specimens having a semi-circular slit, which show the relationship between the stress amplitude and the diameter of slits. The solid symbols represent the specimens failed during fatigue tests. The open symbols represent the specimens which did not fail at up to 10^7 cycles, where the maximum stress amplitude corresponds to the fatigue limit. The asterisk symbols indicate that the specimen failed elsewhere than on the semi-circular slit. The dotted lines in Fig. 6 represent the fatigue limit. The torsional fatigue limit of specimens containing a semi-circular slit of diameter 0.3 mm and 0.6 mm could be increased 156 % and 186 %, respectively by shot peening in contrast to non-shot-peened (Non-SP) specimens.

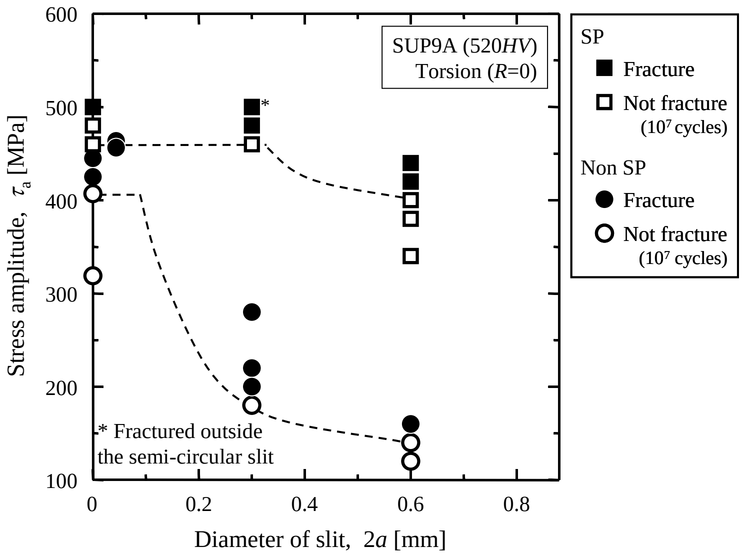


Fig.6 Relationship between stress amplitude and diameter of semi-circular slit. (SUP9A, 520*HV*, torsion, *R*=0).

Size of defects which can be non-damaging by shot-peening

The size of defects which can be non-damaging by SP was evaluated by the following two criterions. (a) Fatigue limit of specimens containing a surface defect is increased by SP within 5 % of the fatigue limit of a non-defect-SP specimen. (b) Specimens containing a surface defect which subjected to SP failed outside the surface defect. Table 4 shows the size of defects which can be non-damaging by SP evaluated by the criterions.

The torsional fatigue limit of the 0.3 mm-holed-SP specimens was equivalent to those of non-defect-SP specimen as shown in Fig.5. However, the 0.3 mm-holed-SP specimens failed from the drilled hole as shown in Fig. 7(a). On the other hand, the 0.2 mm-holed-SP specimen failed outside the drilled hole as shown in Fig. 7(b) Therefore, sizes of drilled hole which can be non-damaging by SP are 0.3 mm in criterion (a) and 0.2 mm in criterion (b).

The torsional fatigue limit of 0.3 mm-slit-SP specimens was equivalent to that of non-defect-SP specimen as shown in Fig. 6. One of a 0.3 mm-slit-SP specimen failed outside the slit and the other failed from the slit. Therefore, sizes of surface slit which can be non-damaging by SP are 0.3 mm in criterion (a) and less than 0.3 mm in criterion (b).

Table 4 Size of defects which can be non-damaging by shot-peening

	Criterion (a) Based of fatigue limit	**Criterion (b)** Based on failure origin
Drilled hole d	0.3 mm	0.2 mm
Surface slit $2a$	0.3 mm	less than 0.3mm

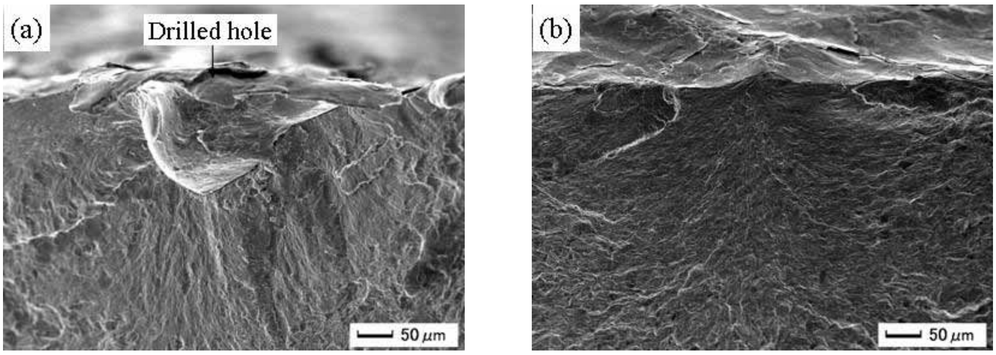


Fig. 7 SEM images of the failure surface, (a) $d=\phi0.3$mm hole, SP, τ_a = 480MPa, N_f = 2.8×10^5. (b) $d=\phi0.2$mm hole, SP, τ_α = 500MPa, N_f = 3.0×10^5.

CONCLUSION

(1) The torsional fatigue limit of spring steel specimens containing a drilled hole of diameter 0.2 mm – 0.8 mm increased 25 % -64 % by shot peening in contrast to non-shot-peened (Non-SP) specimens.
(2) The torsional fatigue limit of spring steel specimens containing a semi-circular slit of diameter 0.3 mm and 0.6 mm could be increased 156 % and 186 %, respectively by shot peening in contrast to non-shot-peened (Non-SP) specimens.
(3) The torsional fatigue limits of 0.3mm-holed-SP specimen and 0.3mm-slit-SP specimen were equivalent to that of non-defect-SP specimen. Thus, drilled hole under 0.3mm diameter and semi-circular slit under 0.3 mm diameter could be non-damaging by SP.

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