Improvement of torsional fatigue limit and rendering surface defect harmless by shot peening for spring steel

K Takahashi\(^1\), M Nakagawa\(^1\), H Koike\(^1\) and H Okada\(^2\)

\(^1\) Yokohama National University, 79-5 Tokiwadai, Hodogaya-ku, Yokohama, 240-8501 Japan
\(^2\) NHK Spring co. ltd., 3-10 Fukuura, Kanazawa-ku, Yokohama, 236-0004, Japan

E-mail: takahashi-koji-ph@ynu.ac.jp

Abstract. The effects of shot peening (SP) on the torsional fatigue limit of spring steel (SUP7) were investigated for specimens with Vickers hardness values of 460, 540, and 670 HV containing a semicircular surface slit. SP was conducted on smooth specimens and specimens containing a semicircular surface slit with a depth of 0.15 or 0.3 mm. Compressive residual stress was introduced into the specimens by SP. Torsional fatigue tests were carried out under a stress ratio of \(R = -1\). The torsional fatigue limits of the shot peened specimens with Vickers hardness values of 460, 540, and 670 HV increased by 8\%–67\%, 33\%–143\%, and 36\%–127\%, respectively, in comparison with the non-shot peened specimens. The maximum depth of the slit that could be rendered harmless by SP was 0.15 mm for the 460 and 670 HV specimens. However, even a slit with a depth of less than 0.15 mm could not be rendered harmless by SP for the 540 HV specimen. Considering the improvement in the torsional fatigue limit and the size of the surface defect that could be rendered harmless by SP, the 670 HV specimen is optimal for practical use.

Keywords: Torsion, Fatigue limit, Shot peening, Spring steel, Surface defect, Residual stress.

1. Introduction
The improvement of fatigue limit of machines and components has been increasing from the viewpoints of fuel efficiency and life span. Shot peening (SP) is a surface treatment method applied to increase the fatigue strength of metals. Compressive residual stress induced by SP prevents fatigue crack propagation. Mechanical components including coil springs, drive shafts and crank shafts, are subjected to cyclic torsion. Since the maximum stress occurs on the surface under torsion and bending, the fatigue crack often initiates from surface defects. The effects of a small surface defect on the torsional fatigue limit have been studied in various metals using specimens containing a small drilled hole [1, 2], a semielliptical surface crack [3], a shallow micronotch [4], and artificial pits [5]. These studies have demonstrated that the presence of surface defects reduces the torsional fatigue limit.

If the surface defects can be rendered harmless from the viewpoint of torsional fatigue limits thorough SP, the reliability of components can be improved. Previous studies have shown that the bending fatigue limit of spring steel (JIS-SUP9A) containing a small drilled hole [6–8] or a semicircular slit [9–11] can be rendered harmless from the viewpoint of the bending fatigue limit. However, little research has been conducted on the SP-induced torsional fatigue limit improvement for high-strength steel specimens containing a crack-like surface defect [12]. In addition, the actual hardness of
automobile parts used in practical situations varies over a wide range. Kuno et al. noted that the improvement ratio of the torsional fatigue limits of spring steel specimens by SP depends on the specimen hardness [13]. It is important to know the size of defects rendered harmless by SP to maintain the component reliability. However, how the hardness affects the size of the defect that can be rendered harmless by SP is not clear. Therefore, in this study, the effect of SP on the torsional fatigue limit of spring steel (JIS SUP7) was investigated for specimens with Vickers hardness values of 460, 540, and 670 HV containing a semicircular surface slit. SP was conducted on smooth specimens and specimens containing a semicircular surface slit with depths of 0.15 and 0.3 mm. Torsional fatigue tests were then carried out under a stress ratio of $R = -1$.

2. Experimental procedure

2.1 Test materials and specimens
The material used in this study was spring steel (JIS SUP7). Table 1 shows the chemical composition of JIS SUP7. Figure 1 shows the shape and dimensions of a fatigue test specimen. Smooth specimens and specimens with a semicircular slit of depth 0.15 or 0.3 mm were subjected to SP. Figure 2 shows the shape of the semicircular slit. The semicircular slit was made by electric discharge machining and was parallel to the axial direction. The width of the slit (0.05 mm) was very small to simulate an initial crack-like surface defect. Next, the specimens were oil quenched at 860 °C and tempered at different temperatures. Table 2 shows the relationship between the tempering temperatures and the Vickers hardness of the test specimens after heat treatment.

| Vickers hardness (HV) | 460 | 540 | 670 |
|-----------------------|-----|-----|-----|
| Tempering temperature (°C) | 500 | 430 | 300 |

2.2 Shot peening conditions and residual stress
After heat treatment, the specimens were subjected to SP. Table 3 shows the SP conditions adopted in this study. The residual stress was measured using the X-ray diffraction method with a Cr Kα beam X-ray spectrum and an X-ray beam injection diameter of 1.0 mm. The distributions of residual stress in the
thickness direction were investigated by alternately measuring the residual stress on the surface and removing the surface layer by chemical etching. The residual stress distributions 45° from the axial directions, i.e., the principal stress directions, were measured.

| Table 3. Shot peening conditions. |
|----------------------------------|
| Peening machine                  | Direct pressure peening |
| Air pressure (MPa)               | 0.42                    |
| Shot diameter (mm)               | 0.7                     |
| Shot hardness (HV)               | 680–750                 |
| Nozzle diameter (mm)             | 5                       |
| Shot time (one side) (s)         | 40                      |
| Shot distance (mm)               | 100                     |
| Coverage                         | 300%                    |
| Arc height (mm A)                | 0.49                    |

### 2.3 Surface roughness and hardness
The surface roughness and strain hardening after SP affect the fatigue strength of metals. Thus, we measured these values for non-shot peened (Non-SP) and shot peened (SP) specimens. Table 4 gives the arithmetic average roughness ($R_a$) and the maximum height of the profile ($R_y$). The surface roughness values increased after SP; however, they were much smaller than the depth of the semicircular slit (0.15 and 0.3 mm). Thus, the effects of surface roughness on the fatigue strength were considered to be small. The surface roughness of SP specimens decreased as increasing the Vickers hardness.

| Table 4. Surface roughness before and after shot peening. |
|----------------------------------------------------------|
| Non-SP | SP |
| $R_a$ (µm) | $R_y$ (µm) | $R_a$ (µm) | $R_y$ (µm) |
| 460 HV | 0.53 | 2.79 | 4.57 | 26.27 |
| 540 HV | 0.68 | 4.16 | 3.64 | 19.49 |
| 670 HV | 0.69 | 3.56 | 1.58 | 10.34 |

Figures 3(a) and (b) show the distributions of the Vickers hardness of the non-shot peened (Non-SP) and shot peened (SP) specimens, respectively. In the Non-SP specimens, the Vickers hardness was almost constant for each specimen regardless of the distance from the surface, as shown in figure 3(a).
In the SP specimens, the Vickers hardness of the 460 and 540 HV specimens increased near the surface because of work hardening caused by the shot impact. However, the 670 HV specimen did not show such an increase in Vickers hardness near the surface. This is because the hardness of the 670 HV specimen is close to that of the shot media (see Table 3).

2.4 Fatigue tests
Torsional fatigue tests were performed on the specimens using a torsional fatigue testing machine (PDF-30, Tokyo Koki Ltd.) at a stress ratio of \( R = -1 \) and a cyclic frequency of 20 Hz. The torsional fatigue limit was defined as the maximum torsional stress amplitude under which the specimen endured \( 10^7 \) cycles. The fracture surfaces of all tested specimens were observed using an optical microscope and a scanning electron microscope (SEM).

3. Experimental results and discussion

3.1 Fatigue test results
Figures 4(a), (b), and (c) show \( S–N \) diagrams that demonstrate the relationship between the stress amplitude \( \tau_a \) and the number of cycles to failure \( N_f \) for the 460, 540, and 670 HV specimens, respectively. The solid and open symbols indicate Non-SP and SP specimens, respectively. The arrows indicate tests in which no fracture occurred in \( 10^7 \) cycles. The torsional fatigue limits are given beside the arrows. The figure demonstrates that torsional fatigue limit and fatigue life were increased by SP. The asterisk symbol (*) indicates that the specimen fractured at the surface but outside the semicircular slit. The pound symbol (#) indicates that an internal fracture occurred. The specimens without symbols fractures from the semicircular slit. The differences of fracture surfaces are discussed in section 3.4.

![Figure 4](image-url)  
Figure 4. \( S–N \) diagrams for torsional fatigue test (SUP7, \( R = -1 \)); (a) 460, (b) 540, and (c) 670 HV.
3.2 Residual stress before and after torsional fatigue tests
The stability of residual stress under cyclic loading is important. Thus, we measured the residual stresses before and after fatigue tests. Figure 5 shows the residual stress distributions before and after the torsional fatigue tests. The residual stress of the Non-SP specimens was much smaller than that of the SP specimens. A small compressive residual stress was induced by machining in all Non-SP specimens. In SP specimens, a compressive residual stress was induced by SP. The solid circles indicate the residual stress before the torsional fatigue tests. The values of the residual stress and crossing point (distance from the surface where the residual stress becomes zero) depend on the specimen hardness. As the specimen hardness increased, the compressive residual stress increased and the crossing point decreased. Okada et al. have reported that the compressive residual stress induced by SP increased in proportion with the Vickers hardness in spring steel (SUP9) from 308 to 746 HV [14]. The open circles indicate the residual stress after the torsional fatigue tests. The fatigue tests caused relaxation of the compressive residual stress in the 460 and 540 HV specimens. In contrast, in the 670 HV specimen, the fatigue tests did not change the compressive residual stress appreciably. Relaxation of the compressive residual stress occurs if the sum of the compressive residual stress and the applied stress exceeds the yield stress of the material [13]. Among the three cases, the yield stress is the highest in the 670 HV specimen, which is greater than the sum of the compressive residual stress and the applied stress. Thus, relaxation of the residual stress did not occur in the 670 HV specimen.

![Figure 5. Residual stress distributions before and after torsional fatigue tests; (a) 460, (b) 540, and (c) 670 HV.](image-url)
3.3 Effects of shot peening on the torsional fatigue limit

Figures 6(a), (b), and (c) show the relationships between the stress amplitude $\tau_a$ and the depth $a$ of the semicircular slit for the 460, 540, and 670 HV specimens, respectively. The solid symbols represent the specimens that failed during the torsional fatigue tests. The open symbols represent the specimens that did not fail in $10^7$ cycles, at which point the maximum stress amplitude corresponds to the torsional fatigue limit. The figures demonstrate that the torsional fatigue limit of the Non-SP specimens decreased with increasing slit depth. It was found that SP increased the torsional fatigue limits of the 460, 540, and 670 HV specimens by 8%–67%, 33%–143%, and 36%–127%, respectively. Compressive residual stresses are the main reason for these increases in the torsional fatigue limit. It is noted that the torsional fatigue limit of the 460 and 670 HV SP specimens with a slit of 0.15 mm depth was equivalent to that of SP specimens without a slit, as shown in figure 6(a) and (c).

![Graphs showing relationships between stress amplitude and depth of the semicircular slit](image)

Figure 6. Relationships between stress amplitude and depth of the semicircular slit (SUP7, torsional, $R = -1$); (a) 460, (b) 540, and (c) 670 HV. In the figure, $a$ denotes the slit depth and $c$ the slit radius.

3.4 Fracture origin

The appearances and origins of the fractures in the tested specimens were examined using an SEM. Figures 7 and 8 show SEM images of the fracture surfaces of specimens with a semicircular slit of depth 0.15 and 0.3 mm, respectively. The mode I fatigue cracks propagated in a direction perpendicular to the principal stress direction, i.e., $\pm 45^\circ$ from the axial direction. The Non-SP specimens fractured at the semicircular slit regardless of the slit depth. The semicircular slits can be clearly observed in the Non-
SP specimens. The SP specimens with a slit of 0.3 mm depth fractured at the semicircular slit, as shown in figure 8. The semicircular slits were deformed by SP. The crack initiation site depended on the specimen hardness in the SP specimens with a slit of 0.15 mm depth. The 540 HV specimens fractured at the slit, whereas the 460 and 670 HV specimens fractured outside the slit. The crack initiation sites in all 670 HV SP specimens were matrix cracking at 0.2–0.3 mm depth where the tensile residual stress observed (see figure 5(c)). Inclusions were not observed at the crack initiation sites.

|       | Non-SP | SP |
|-------|--------|----|
| 460HV | ![Fatigue fracture surface after test; slit depth = 0.15 mm.](image1) | ![Fatigue fracture surface after test; slit depth = 0.15 mm.](image2) |
| 540HV | ![Fatigue fracture surface after test; slit depth = 0.15 mm.](image3) | ![Fatigue fracture surface after test; slit depth = 0.15 mm.](image4) |
| 670HV | ![Fatigue fracture surface after test; slit depth = 0.15 mm.](image5) | ![Fatigue fracture surface after test; slit depth = 0.15 mm.](image6) |

Figure 7. Fatigue fracture surface after test; slit depth = 0.15 mm.

|       | Non-SP | SP |
|-------|--------|----|
| 460HV | ![Fatigue fracture surface after test; slit depth = 0.3 mm.](image7) | ![Fatigue fracture surface after test; slit depth = 0.3 mm.](image8) |
| 540HV | ![Fatigue fracture surface after test; slit depth = 0.3 mm.](image9) | ![Fatigue fracture surface after test; slit depth = 0.3 mm.](image10) |
| 670HV | ![Fatigue fracture surface after test; slit depth = 0.3 mm.](image11) | ![Fatigue fracture surface after test; slit depth = 0.3 mm.](image12) |

Figure 8. Fatigue fracture surface after test; slit depth = 0.3 mm.
It is important to observe non-propagating cracks of the specimens that did not fracture during fatigue test because the non-propagating crack sizes were related to the acceptable crack sizes \([9, 11]\). We tried to observe non-propagating fatigue cracks of the specimens tested under the torsional fatigue limit. However, non-propagating cracks could not be observed probably due to the wear of the mating crack surfaces under cyclic shear loads and compressive residual stress. In the case of bending fatigue, non-propagating cracks were clearly observed in the spring steel specimens tested under the bending fatigue limit \([6-11]\). In this study, the fatigue cracks propagated under mode I (see figures 7 and 8). Thus, it is thought that the torsional fatigue limit was determined by the threshold condition for non-propagation of fatigue cracks similar to the case of bending fatigue tests.

### 3.5 Size of defect that can be rendered harmless by shot peening

In this section, we discuss how the specimen hardness affects the sizes of semicircular slits that can be rendered harmless by SP. If the fatigue test results of an SP specimen with a semicircular slit meet either of the following two conditions, the slit is considered to have been rendered harmless.

**Condition (a):** The fatigue limit increased up to more than 95% of that of a SP specimen without a semicircular slit.

**Condition (b):** The specimen fractured outside of the slit.

These conditions were proposed by the “Acceptable Defect Size Research Committee” in Japan Society of Spring Engineers \([7]\). For the 460 and 670 HV specimens, the torsional fatigue limit of the SP specimens with a slit of 0.15 mm depth was equivalent to that of SP specimens without a slit (see figures 6(a) and (c)). Moreover, these specimens fractured outside of the semicircular slit (figure 7). However, the SP specimens with a slit of 0.3 mm depth fractured at the semicircular slit (figure 8). Therefore, the depth of a surface slit that can be rendered harmless by SP was 0.15 mm for the 460 and 670 HV specimens according to conditions (a) and (b). It is reported that the surface slit with a 0.15 mm depth was rendered harmless by SP in 500 HV spring steel SUP9A \([12]\). Thus, SUP7 tested in our experiments shows similar results. The surface slit of 0.15 mm depth reduced the torsional fatigue strength by 35% and 36%, respectively, in the 460 and 670 HV specimens. Thus, SP is a useful surface treatment technique for increasing the structural integrity of components subjected to cyclic torsion, even if the components have a detrimental surface defect.

In the 540 HV specimens, the torsional fatigue limit of the SP specimens with a slit of 0.15 mm depth was lower than that of SP specimens without defects (figure 6(b)). Moreover, the SP specimens with a slit of 0.15 mm depth fractured at the semicircular slit (figure 7). Therefore, in the 540 HV specimen, the surface slit of 0.15 mm depth was not rendered harmless by SP according to conditions (a) and (b). However, the torsional fatigue limit was increased by 143% in this specimen.

From the above results, it was found that the defect size that can be rendered harmless depends on the specimen hardness. Considering the torsional fatigue strength and defect size that can be rendered harmless by SP, 670 HV is a suitable Vickers hardness value for components.

### 4. Conclusions

1. SP increased the torsional fatigue limits of the 460, 540, and 670 HV specimens by 8%–67%, 33%–143%, and 36%–127%, respectively. Compressive residual stresses are the main reason for this increase in the torsional fatigue limit.

2. In the 460 and 670 HV specimens, the torsional fatigue limit of the SP specimens with a slit of 0.15 mm depth was equivalent to that of SP specimens without defects. Moreover, these specimens fractured outside of the slit. Therefore, the size of the surface slit that can be rendered harmless by SP was 0.15 mm.

3. In the 540 HV specimens, the torsional fatigue limit of the SP specimens with a slit of 0.15 mm depth was lower than that of SP specimens without defects. Moreover, the SP specimens with a slit of 0.15 mm depth fractured at the slit. Therefore, the depth of the surface slit that can be rendered harmless was less than 0.15 mm for the 540 HV specimens.
(4) SP is a useful surface treatment technique for increasing the structural integrity of components subjected to cyclic torsion, even if these components have a detrimental surface defect.

Acknowledgment
A part of this research has been conducted as a collaborative research project in a research center for Green Material Innovation at Yokohama National University. The authors gratefully acknowledge members of the collaborative research project.

References
[1] Endo M and Murakami Y 1987 Effects of an artificial small defect on torsional fatigue strength of steels *J. Eng. Mater. Technol.* **109** 124–9.
[2] Billaudeaux T, Nadot Y and Bezine G 2004 Multiaxial fatigue limit for defective materials: mechanisms and experiments *Acta Mater.* **52** 3911–20.
[3] Murakami Y and Takahashi K 1998 Torsional fatigue of a medium carbon steel containing an initial small surface crack introduced by tension-compression fatigue: Crack branching, non-propagation and fatigue limit *Fatigue Fracture Eng. Mater. Struct* **21** 1473–84.
[4] Beretta S, Foletti S and Valiullin K 2011 Fatigue strength for small shallow defects/cracks in torsion *Int. J. Fatigue* **33** 287–99.
[5] Wakita M, Kuno T, Amano A, Nemoto A, Saruki K and Tanaka K 2007 Study on predicting formula for torsional fatigue strength of spring steel—effect of environment, notch and hardness *Transactions of Japan Society of Spring Engineers* **2007** 1–7.
[6] Takahashi K, Amano T, Miyamoto T, Ando K, Takahashi F, Tange A, Okada H and Ono Y 2007 Improvement of fatigue strength by shot peening for spring steel specimens containing an artificial surface defect *Transactions of Japan Society of Spring Engineers* **2007** 9–13.
[7] Acceptable Defect Size Research Committee 2008 The research committee report of the acceptable defect size for spring steel, *Transactions of Japan Society of Spring Engineers* **2008** 57–66.
[8] Takahashi K, Hayashi T, Ando K and Takahashi F 2010 Evaluation of acceptable defect size by shot peening based on fracture mechanics *Transactions of Japan Society of Spring Engineers* **2010** 25–30.
[9] Takahashi K, Amano T, Ando K and Takahashi F 2011 Improvement of fatigue limit by shot peening for high-strength steel containing a crack-like surface defect *Int. J. Struct. Integr.* **2** 281–92.
[10] Nakagawa M, Takahashi K, Osada T, Okada H and Koike H 2014 Improvement in fatigue limit by shot peening for high-strength steel containing crack-like surface defect (influence of surface crack aspect ratio) *Transactions of Japan Society of Spring Engineers* **2014** 13–18.
[11] Yasuda J, Takahashi K and Okada H 2014 Improvement of fatigue limit by shot peening for high-strength steel containing a crack-like surface defect: Influence of stress ratio *Int. J. Struct. Integr.* **5** 45–59.
[12] Takahashi K, Okada H and Ando K 2012 Effects of shot peening on the torsional fatigue limit of high strength steel containing an artificial surface defect *Int. J. Struct. Integr.* **3** 274–84.
[13] Kuno T, Wakita M, Hasegawa T, Saruki K and Tanaka K 2010 Effect of hardness and shot peening on torsional fatigue strength of high strength spring steel *Transactions of Japan Society of Spring Engineers* **2010** 19–24.
[14] Okada H, Tange A and Ando K 2003 Relationship among specimen's hardness, residual stress distribution and yield stress on the difference of shot peening methods *J. High Pressure Inst. Japan* **41** 233–42.