# Improve Fatigue Limit on Coil Spring

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## Introduction

To increase the fatigue strength of coil spring by shot peening has been discussed in many papers, the major topic was to correlate the peening intensity with fatigue strength in terms of redistribution of residual stress and change of surface topography. However, failure analysis was not so emphasised in the previous works and the leading factor which is responsible to the increase of fatigue strength was not clarified. Since fatigue test for coil spring is tedious and time consuming, it would be benefitial to the practical application to find the vital factor for the quality control.

Paper (1) summerized the effect of shot peening for coil spring with a broad spectrum of testing parameters and found that with the increase of peening intensity, the surface roughness increases; the peak value of compressive residual stress holds in constant while the surface value decreases; the depth of the peak value shows little change but the total depth increases. The fatigue strength depends on the size of coil wire, with the increase of peening intensity, for the diameter smaller than 2mm, a maximum fatigue strength corresponds to a certain peening intensity; for 3mm, fatigue limit shows little effect with a large extent of peening intensities; for those diameter larger than 3mm, fatigue strength gradually increases with the increase of peening intensity(1,2). Nevertheless, it seems to be not appreciable so far to set up a correlation between residual stress distribution and surface roughness with the fatigue limit for coil spring.

Leaf spring, on the other hand, exhibits reasonable good relation with peening intensity. Paper(3) presented an equation correlating the integral value of surface residual stress and the fatigue limit. Paper(4) found surface roughness is the leading factor for the fatigue strength of leaf spring. The difference of testing results between coil and leaf spring could be resulted from the following facts: First, the surface layer of leaf spring is usually decarburized and the fatigue crack initiates there, it should be benefitial to improve the surface strength by reducing the roughness or increasing the compressive residual stress. Second, The fatigue fracture of leaf spring is caused by normal stress under bending, biaxial compressive residual stresses are in the principle loading stress plane, so the Goodman or Dang Van relation can be employed for fatigue limit evaluation. Coil spring is suffered from torsion and shear stresses, since the mean stress does not change shear fatigue behavior(5), the compressive residual stress would show little contribution on the shear fatigue strength too. Decarburization is negligible for coil spring, so its strengthening behavior is different. It would be helpful to find out the fracture mechanism prior to the prediction of peening parameters for coil spring production. In this experiment, different processing ways were carefully selected to obtain different depths and magnitudes of residual stress and different surface roughnesses as well. Fracture characteristics were examined by fractography, so as to find out the effects of above factors on the fatigue behavior for coil spring.

## Experimental Procedures

In order to save the boring fatigue test, only three groups of coil spring were chosen. A normal heat treatment was applied for unpeened coil spring which were taken for comparison. The other two groups were shot peened, the first group with the same hardness of unpeened specimens were peened in a low intensity to induce high but shallow compressive residual stress. The second group with lower hardness value were peened with high intensity to build low but deep residual stress, then this group was brought to be galvanized to further decrease the surface compressive residual stress value.

Coil springs were made of 0.65–0.70%C wire with 3mm in diameter. The total number of coil ring of a spring is 7, its free height is 50mm with a diameter of 20mm. Steel shots were used for peening. The states of testing groups are as Tab. 1

Tab. 1 States of samples

| Group | Hardness (HRc) | shot peening<br>Shot size (mm) | Intensity mmA | Galvanizing |
|---|---|---|---|---|
| A | 48 | No | No | No |
| B | 48 | 0.5 | 0.25 | No |
| C | 43 | 0.7 | 0.35 | Yes |

Residual stress was measured by x-ray diffraction method on Rigaku MSF-2M machine with Cr-k$\alpha$ radiation, $\sin^2\psi$ method. Measurements were carried out on the inner surface of coil rings. Residual stress distributions were obtained by electrolytical etching. Fracture surfaces were examined on JSM-35C scanning electronmicroscope. Fatigue tests of coil spring were performed on a self-made vibrator with eccentric press. The vibration amplitude can be adjusted by the eccentricity of driving shaft. The stress ratio was kept in 0.1.

## Experimental Results

a. Fatigue test
Six shear stress levels from 680 to 855 MNm$^{-2}$ with 35 MNm$^{-2}$ interval were selected for fatigue test and $10^7$ cycle was taken as basis. Each group consisted 12-20 samples. The stress level at which 85% samples were survived after $10^7$ cycles was determined as fatigue limit. If the confidence was not exactly 85% at one stress leval, interpolation was used. Fatigue shear stress limits are shown in Tab.2.

Tab. 2 Fatigue limits in shear stress

| Group | A | B | C |
|---|---|---|---|
| Fatigue limit (MNm$^{-2}$) | 694 | 812 | 855 |

b. Fractography
11 fracture surfaces have been observed for Group A. Cracks initiated mostly at the inner surfaces of coil rings, only about one quarter were at the lateral surfaces. Cracks were nucleated at the very surfaces (Fig.1A) except one, which was 40µm beneath the surface.

More than 30 fracture surfaces for Group B showed that all cracks initiated at the subsurface of inner part rings, the depths of crack origin were with in 50 to 100µm,. A stepwise crack path can be detected as in Fig.1B.

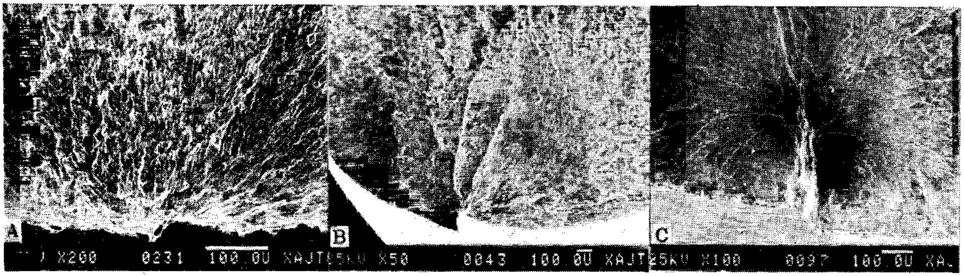

Fig. 1: Fracture surfaces of Group A, B. and C.

10 fracture surfaces of Group C showed the cracks were mainly initiated in the inner surfaces and all nucleated in the subsurfaces. The depth for those passed $10^7$ at $855 MNm^{-2}$ was 200 µm, with the same stress level there were two springs whose cyclic number only lasted about $3x10^6$ showed the fatigue origins 100 µm beneath the surface. A normal fracture feature is shown in Fig. 1C.

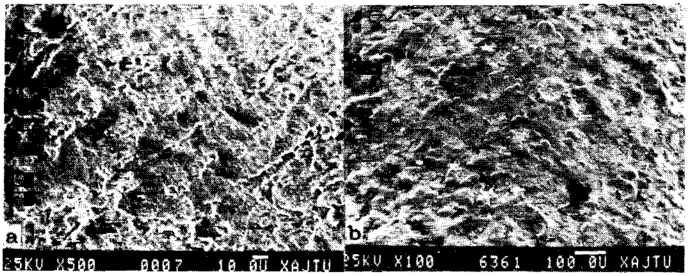

Fig. 2: Surface topography of a, Group A, b, Group C.

All samples in this experiment were broken by normal stress, it was characterized in the crack path $45^0$ degree to the axial direction of coil wire, thus the subsurface crack formed a stepwise on the surface.

c. Surface topography and roughness

Scratches and dents were observed on the unpeened A samples as Fig.2a, but disappeared on the peened surface. (Fig.2b) Results of roughness test are listed in Tab.3.

Tab. 3 Surface roughness

| Group | A | B | C |
|---|---|---|---|
| $R_z$(µm) | 0.3 | 0.3–0.6 | 0.3–0.4 |

d. Residual stress

Residual stress distribution curves of Group B and C are shown in Fig.3. The difference of two curves are as expected. The compressive residual stress is higher in magnitude but smaller in depth for B in comparison with C, of which the surface stress value slightly in tension is due to galvanizing after shot peening.

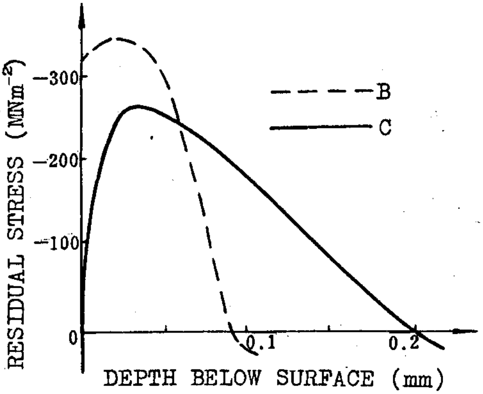

Fig. 3: Residual stress distributions

e. Hardness
Hardness did not change very much after shot peening. The hardness data for B and C before and after shot peening were situated in the scatter bands with an average values as Tab.1.

## Discussions

Fractography shows the fracture surface, inclined 45° degree to the wire axis, should be seperated by the normal stress and it agrees with the result of (6), where a torsion bar was conducted with reverse shear load but its fracture was caused by normal stress and characterized in 45° degree to the bar axis. Besides, it is known that shear strength depends on hardness and biaxial residual normal stresses will be of little effect. In this test, Group B with the same original hardness as A did not hardened much after shot peening, but its fatigue limit increases intensively, so the normal stress fracture is again confirmed, even the loading stresses are basically shear for coil spring.

For shot peened samples cracks are always initiated in the subsurface layer, their locations are associated with the residual stress distribution curves and appear in the region where compressive residual stress drops sharply, say 50 to 100 µm for Group B and 200 µm for Group C. The deeper the fatigue origin the higher the fatigue limit, regardless the low compressive residual stress value and even a slight tensile stress in the very surface as Group C.

The location of fatigue origin can be predicted by (7).

$$(\Delta\sigma_a)_{local} = -\sigma_{-1}/\sigma_b \cdot (\sigma_r)_{local}$$

Here, $(\Delta\sigma_a)_{local}$ is the increment of local fatigue strength.
$\sigma_{-1}$ is the reverse bending fatigue limit without residual stress.
$\sigma_b$ is the ultimate strength.

( $\sigma_r$ )$_{local}$ is the local residual stress value in different depth.
$\sigma_{-1}/\sigma_b$ is constant for a material, if it equals 0.5 according to (8), the local strength and loading stress through the depth are shown in Fig.4

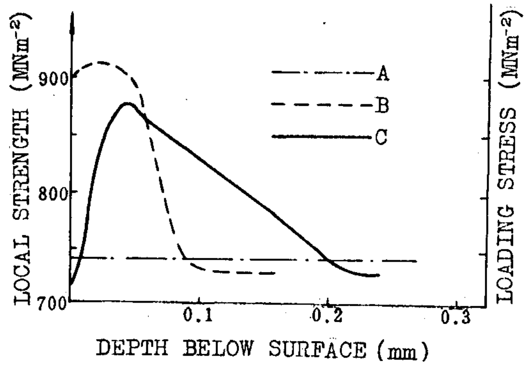

Fig. 4: Local strength and loading stress through depth

Normal loading stress in Fig.4 is obtained with shear stress of 855 MNm$^{-2}$ For B and C, fatigue origins are predicted at about 70 and 180 $\mu$m respectively. For A, cracks initiate at the surface, that agrees well with the experimental data. Once the cracks initiated beneath the surface, the loading stress is lower than that on the surface and it grows in vacuum with a higher resistance than in the air, so the fatigue strength increases. Crack initiation for torsion fatigue only holds a small fraction of fatigue life, thus the deeper the crack, the longer it breaks through the surface, and the higher the fatigue limit.

The highest fatigue limit for C explains that the effects of hardness and very surface strength are less important in comparison with residual stress, when the crack initiates under the surface. But for Group A, crack grows from the surface, surface quality is important.

## Conclusions

1. The loading stress for coil spring is shear stress though, its fatigue fracture is caused by normal stress. Compressive residual stress plays a more important role than hardness in the range of 40 to 50 HRc.
2. Surface defects act as fatigue origin for unpeened spring, fatigue strength can be increased by improving surface quality. Shot peening turns the fatigue origin into subsurface, surface quality will contribute little on the fatigue behavior.
3. When crack initiates beneath the surface, the fatigue strength can be increased by increasing the depth of compressive residual stress to a certain extent, the magnitudes of surface and peak values of residual stress are less important.
4. If the crack origins located in the different sites, their fatigue limits cannot be evaluated by Goodman or Dang Van relation.

## References

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