Residual Stress Concentration and its Effect on Notch Fatigue Strength

Zhang Dingquan, Xu Kewei, Wang Xike, Hu Naisai
Research Institute for Strength of Metals, Xian Jiaotong University, Xian, China.

Introduction

It has been concluded that shot peening can greatly improve the fatigue strength particularly for notched parts(1). Kloos found the notched fatigue strength could be even higher than the highest normal fatigue strength after surface rolling(2). Yet it is still puzzle how to explain this fact.

Finite element analysis showed that residual stress concentrates at the root of a notch. With the decrease of notch radius the maximum value of residual stress shifts away from the surface of the notch root(3). However, only very few experimental results were presented for the distribution of residual stress at sharp notch, due to the difficulty of measurement.

Wohlfahrt found, with the same peening parameter, for a case hardened steel the compressive residual stress value at the surface of the notch was the same as that of the flat specimen, but the maximum value in the layer below the notch surface was much higher than that of flat one (4). Bergstrom reported no significant difference of residual stress for the smooth specimen from the notched one with 2.5mm radius. The residual stress distribution in the axial direction almost overlapped with the curve in the tangential direction, it was, again, similar to that of smooth specimen after shot peening. In addition. Bergstrom found that shot peening did not contribute much for the notch fatigue limit of high temperature tempered steel, due to the relaxation of compressive residual stress and the relaxing rate was the same for smooth and notched specimen at the same local stress (5). The difference of experimental results presented in the literature could be, in part, explained by the difference of yield strength for the tested material, if the compressive residual stress is easy to fade away, the fatigue strength will show little improvement. However, there was an appreciable amount of compressive residual stress existed at the load level of fatigue limit for (5), it is not clear why the notch fatigue limit did not increase much.

Usually, loading stress concentration is bigger in the axial direction than in the tangential direction, is there any difference between the concentration of loading stress and residual stress? Since there was no correlation for the compressive residual stress and fatigue behavior for high strength specimen with a notch, it would be interesting to study the concentration factor of residual stress after shot peening and its effect on fatigue strength for a low temperature tempered steel.

This paper is focused on the measurement of residual stress distribution for a small radius notch and to find out what is happening during cyclic loading. The notch radius in this experiment is 1mm in a 8mm of diameter specimen. It could be easier to make the stress measurement at a large radius notch, but to keep an appreciable stress concentration factor the specimen size should be bigger, then the fatigue test becomes tough.

Specimen and Experimental Procedures

Material used in this experiment was medium carbon steel with 0.43%C and 0.98% Cr.

Steel bars were machined into rotating bending specimens with 8mm in diameter, the notch radius was 1mm. All specimens were heat treated in a salt bath at 860°C, then oil quenched and 200°C tempered. 1mm redius notch was machined after heat treatment.

Mechanical properties of test specimen are listed in Tab. 1

Tab. 1 Mechanical properties of the tested material

Ultimate strength (MNm^{-2})	Yield strength (MNm^{-2})	
1970	Pull	Push
	1515	1720

The diameter of steel shot for peening was 0.5–0.8mm. The specimens were rotating with 1 rpm in peening. The Almen intensity was 0.42A mm.

Fatigue tests were performed on a rotating bending machine. The stress level at which 50% specimens survived after 10^7 cycles was taken as fatigue limit. Residual stress was measured on a DMax-3A diffractometer with ψ -goniometer method for the axial direction and Ω -goniometer method for the tangential direction. A pinhole collimator was used to result in a well concentrated x-ray spot of 0.5mm diameter at the notch. Since the beam size of x-ray was comparable to the radius of the notch, the incident angle was only an average value, close attention has to be paid on the specimen setting. Experimental results showed that error was induced mostly from the displacement in the axial direction (6). A magnifier of 5x was attached on the ψ -goniometer for specimen alignment. A flat specimen with known stress value was checked on this setting prior to the measurement. A well annealed notched specimen was examined with this attachment and its result was satisfactory. Since the error by axial displacement can be compensated in the + ψ and - ψ directions, 0, ±15, ±20, ±25, ±30 and ±35, ie. 11 angles were taken for each stress measurement. The deviation of stress value calculated with 0.2mm displacement in the axial direction were less than $100MNm^{-2}$ whilest the actual displacement in this measurement could be aligned less than 0.10mm.

A fine focus (0.4 x 0.8mm)Cr x-ray tube with V filter was used. The peak position was determined with five point parabolic method, the accumulated counts for each step were higher than 5000.

Residual stress distributions were measured with electrolitical etching. No correction was available for the removal of the surface layer at the notch due to its geometry. For comparison, correction was not made on the smooth specimen either.

Results and Discussions

The rotating bending fatigue limits for smooth and notched specimens are listed in Tab. 2

Tab. 2 Fatigue limits for smooth and notched specimens

	Smooth		Notched	
	Ground	Peened	Ground	Peened
Fatigue limit (MNm^{-2})	640	730	525	645
Increment % after peening	-	14	-	23

The increment of fatigue limit is larger for notched specimen than for smooth one after shot peening.

Fractography with SEM observation showed that the fatigue crack initiated in the depth of 30µm beneath the surface for ground specimens but right at the bottom of the peening dent for shot peened specimens. (Fig. 1 a and b)

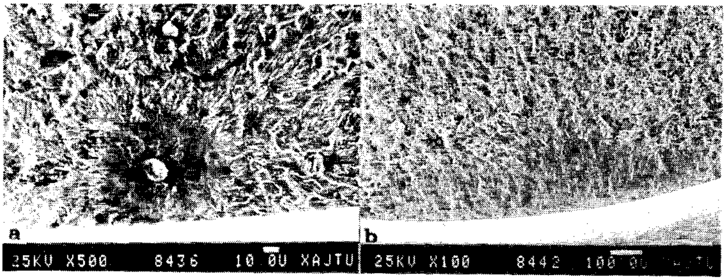


Fig. 1 Fracture surfaces of notched specimens
a. Ground b. Shot peened

An extended low crack growth rate region on the shot peened fracture surface is associated with high fatigue strength.

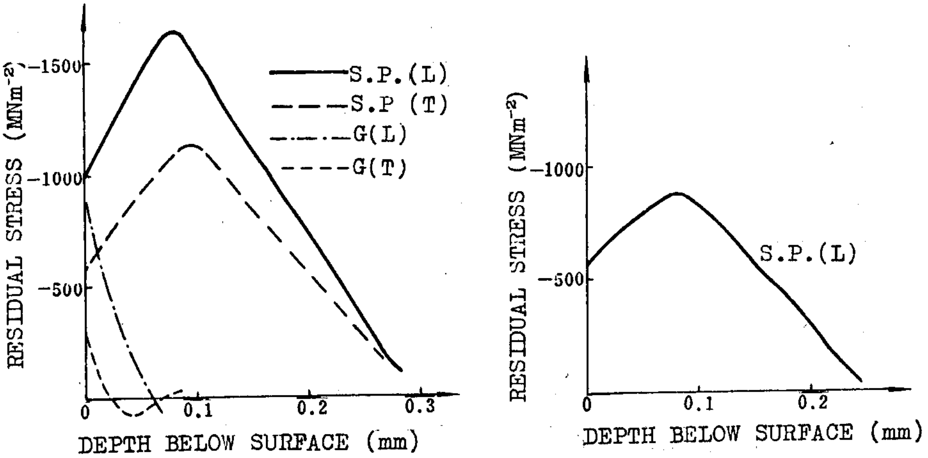
Fig. 2a shows the residual stress distributions of ground and shot peened specimens in the notched parts. Since the notch was cut after heat treatment, the ground specimen bears fairly high compressive residual stress but only in a very shallow depth.

Fig. 2a and b show residual stress concentration effect does appear in this low tempereature tempered steel specimen, that agrees with the results of (4).

The axial stress concentration factors vary within 1.94 to 1.74 from the surface to the site of maximum value, and is close to the static loading stress concentration factor of 1.73.

Tangential residual stress concentration also appeared in Fig. 2 shows the nature of concentration for residual stress is somewhat different from loading stress. On account of equal biaxial residual stress induced by shot peening for the flat specimen and the different constrains for notched part, one may think the sharper the notch radius the greater the difference of stress concentration between axial and tangential directions.

The effect of residual stress on notch fatigue strength depends on its relaxation. Fig. 3 shows the residual stress distributions after cyclic loading at the fatigue limit stress level.



(a) (b)

Fig. 2 Residual stress distributions of specimens before fatigue
a. Notched b. Smooth

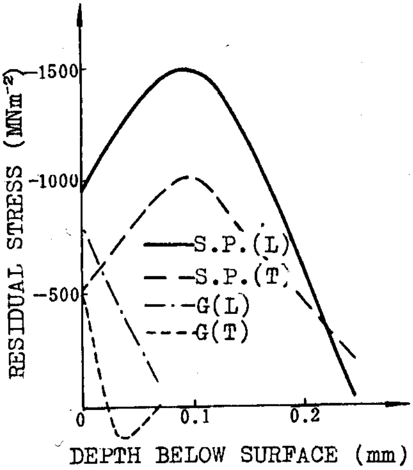


Fig. 3 Residual stress distributions of notched specimens after fatigue.

It is strange that the compressive stress only decays slightly, if one superimposes the peak loading compressive stress with the peak residual compressive stress for shot peened specimen, its sum can reach as high as 2600MNm^{-2} and the yield strength of material is about 1720MNm^{-2}.

Von mises criterion is always employed for the yield of biaxial stress state, it assumes that the yield strengths for compression and tension are equal, and can be expressed as an ellipsoid in Fig. 4. The sum of the compressive residual

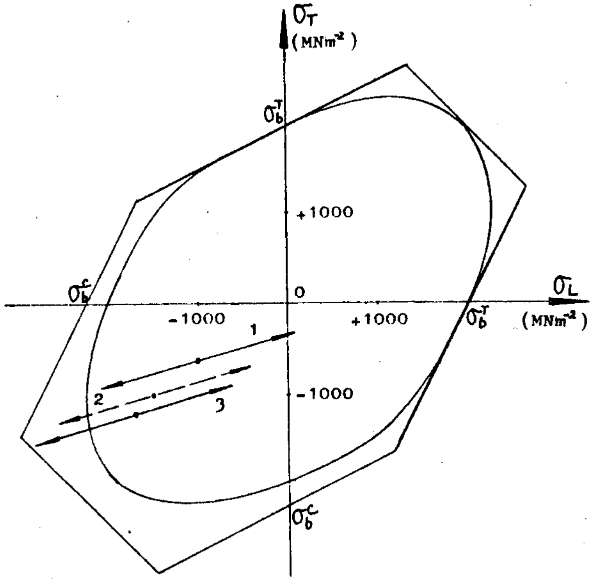


Fig. 4 Von Mises and biaxial principle shear stress criteria for residual stress relaxation
1- At the surface of notch root
2- 0.08mm below the notch surface after 10^7 cycles at fatigue limit
3- As 2 but before fatigue

stress and loading stress after 10' cycles is still outside the rim of this ellipsoid for static yielding. It is obviously irrational without any relaxation of residual stress under static loading even after millions of cycles. Recently, a biaxial principle shear stress criterion was suggested (7). It claims that under complex stress state yield is justified by the sum of two principle shear stresses and the different yield strengths for push and pull, particularly for brittle material should be taken into account. The shot peened surface has been strengthened, its yield strength is promoted close to the ultimate strength, therefore the yield strength should be replaced by the ultimate strength. The following equations are the criteria for static yielding.

$$\begin{aligned} \sigma_L - \tfrac{1}{2}\sigma_T &= \sigma_b^T \text{ or } \sigma_b^c \\ \tfrac{1}{2}(\sigma_L + \sigma_T) &= \sigma_b^T \text{ or } \sigma_b^c \qquad \text{Equ.1} \\ \sigma_T - \tfrac{1}{2}\sigma_L &= \sigma_b^T \text{ or } \sigma_b^c \end{aligned}$$

Here, σ_L and σ_T are axial and tangential stresses, σ_b^T and σ_b^c are ultimate strengths for tension and compression. Since it is difficult to obtain the ultimate compressive strength, we assume the ratio of yield strengths for compression and tension is equal to the ratio of ultimate strength for them and the stress concentration factor at the depth of the maximum compressive residual stress is equal to that at the root of the notch, its value can be calculated with

$$\sigma_n = K_t \cdot S \qquad \text{Equ.2}$$

here, σ_n is the local stress at the notch root, K_t is the stress concentration factor and S is the nominal stress.

The hexagon-like criterion by Equ.1 is also shown in Fig. 4. The maximum value of the sum of residual and loading stresses after fatigue is a distance off inside the rim of biaxial principle shear stress criterion, it agrees basically with the requisite for cyclic relaxation.

A notch not only holds high compressive residual stress but also keeps it from relaxation, so the notch fatigue strength can be greatly improved after shot peening.

Since the magnitude of compressive residual stress is generally larger than the tensile loading stress within 300μm from the surface of the notch, material in this region is suffered from push-push except a very thin layer near the surface, where is under heavy push with slight pull. It may explain why the crack initiates there, and propagates with low rate under push-push stress state.

It is now recognized that a crack can grow under the push-push loading. With the increase of peak compressive loading stress, the fatigue limit decreases (8). Crack propagation rate under compressive stress state is of course, far less than in the tensile stress field. Thus, the fracture surface exhibits slip decoherence in this region as shown in Fig. 1b.

Conclusions

1. Residual stress does concentrate at the notch. The axial compressive residual stress after shot peening holds a stress concentration factor close to that of loading stress. Tangential residual stress also concentrates in the notch but its magnitude is smaller than that of the axial stress.

2. Residual stress relaxation is mainly due to plastic deformation with a macroscopic scale yielding, which can be justified by the biaxial principle shear stress criterion.

3. With the geometrical effect, the residual stress kept in the notched part can be much higher than that for smooth part.

4. High compressive residual stress is the major factor which keeps the crack from propagation and increases the fatigue limit to a great extent.

References

(1) H.O. Fuchs: Proceedings of First International Conference on Shot Peening (1981) 323.
(2) K.H. Kloos: Z. Werkstoffkundtech 12 (1981) 359.
(3) R.H. Todd: Experimental Mechanics 12 (1971) 548.
(4) H.Wohlfahrt: Residual Stress and Stress Relaxation (1982) 71.
(5) J.Bergstrom: Proceedings of Second International Conference on Shot Peening (1984) 241.
(6) To be submitted.
(7) Yu, M. H: Int. J. Mech. Sci. V.25 (1983) 71.
(8) Yu, M. H: Int. J. Fatigue 8 (1986) 9.