RELATION BETWEEN SHOT-PEENING RESIDUAL STRESS DISTRIBUTION AND FATIGUE CRACK PROPAGATION LIFE IN SPRING STEEL

Akira TANGE
NHK Spring R & D Center Inc.
Noritoshi TAKAMURA
Precision Spring Division NHK Spring Co.,Ltd.,Japan

ABSTRACT
We performed the following study to examine the influence of the residual stress distribution by shot-peening on the fatigue crack propagation life.The results we obtained are as follows;
(1) To define the threshold conditions of small crack propagation in spring steels, we proposed a method which consists of applying the hardness and stress ratio dependency to Haddad's consolidation.
(2) It is very important to raise the surface residual stress for improving the fatigue crack propagation life.
(3) Most of the fatigue crack propagation life is spent while the crack propagates from the surface to the position where the compressive residual stress is maximum.
(4) The nearer to the surface the position where the compressive residual stress is maximum, the longer fatigue crack propagation life is extended.
(5) The predicted S-N curve by this method shows good correspondence with the actual results of the rotary bending fatigue tests.

Key words
SHOT-PEENING , RESIDUAL STRESS , FATIGUE , SPRING STEEL ,
FRACTURE MECHANICS , SMALL CRACK , CRACK PROPAGATION LIFE ,

1. INTRODUCTION

The distribution of residual stress due to shot-peening is specific in that certain peening conditions and spring hardness reduce residual stress on the surface of the spring and give maximum stress inside.It has therefore not been explained in detail whether the compressive residual stress distribution pattern is the most suited method to longer fatigue life. Further, such high-strength material as spring steel has been characterized by the fatigue fracture causing by small cracks. Experimental difficulties do not allow to thoroughly study and grasp the threshold conditions of the small crack propagation in high-strength materials.

In this paper therefore the threshold conditions of the fatigue crack propagation due to the small cracks were decided to have been identified through an extension and application of such factors as hardness and stress ratio dependency, to Haddad's formulae assuming the residual stress to be equivalent to the mean stress.

The crack arrest effect of the residual stress was determined by an extrapolative application, to the threshold condition of small crack propagation of the relationship between the crack propagation ratio and and stress intensity factor based on the linear fracture mechanics, as obtained for large crack.

2. THRESHOLD CONDITIONS OF FATIGUE CRACK PROPAGATION DUE TO SMALL CRACK IN SPRING STEEL

2.1 CHARACTERISTICS OF SMALL CRACKS

It is generally recognized that the linear fracture mechanics allows us to define the threshold condition of the fatigue crack propagation from large crack, namely the fatigue limit of the materials suffering cracks by the threshold of stress intensity factor range (ΔK_{th}) peculiar to materials and their strength[1]. The very small crack lead to fatigue fracture in such high-strength materials as spring steels. It has been reported that in the case of these materials the fatigue crack propagation is caused by the value of ΔK_{th} based on the small cracks smaller than based on the larger cracks . And the smaller the crack length, the ΔK_{th} presents the smaller values [2].It has been discussed that the reasons why it is so is that the small crack do not meet the conditions of small scale yielding which is a presupposition in the linear fracture mechanics; that the size of cracks equals almost to grain size therefore making it hard to hold the hypotheses of isotropy and homogeneity ; or that the fatigue crack closure is too small. In some reviews it has been described that a negative evaluation results if the threshold of stress intensity factor range as measured in large cracks (referred to as "$\Delta K(L)_{th}$") is taken into the threshold conditions of fatigue crack propagation [3][4].

There are recently a number of reports where the threshold conditions of fatigue crack propagation are obtained from the stress intensity factor range (the effective stress intensity factor range ΔK_{eff}) that can significantly contribute to crack propagation by a strict measurement of fatigue crack closure [5]. It is however extremely difficult and accordingly inconvenient to strictly measure the small crack clousure of the order of several scores of microns.

Murakami [6] has overcome such a difficulty consolidating, in his report, a variety of experimental results obtained in a number of linear fracture mechanics, thereby inducing the threshold condition of fatigue crack propagation only out of hardness and crack length. His report however does not deal with the effect of the residual stress, the subject of this paper.

Haddad [7] however has proposed, as formulae (1) and (2), the fatigue limit of small crack ($\Delta\sigma_{th}/2$) introduced, as an intermediate, from the fatigue limit ($\Delta\sigma_w/2$) of a defectless smooth material and from that in large crack, $\Delta K(L)_{th}$. The threshold stress intensity factor range in small crack (referred to as " $\Delta K(S)_{th}$ ") results therefore in the formula (3) below, where the calculation formula for the stress intensity factor range is applied as $\Delta K = \alpha\Delta\sigma\sqrt{(\pi a)}$. It should be noted here that the fatigue limit can be obtained rather readily in the case of low-strength smooth material, but that an true fatigue limit is experimentally difficult to obtain in high-strength materials due to the breakage caused by non-metallic inclusion, which in turn is caused by increased fatigue notch sensitivity.

$$\Delta\sigma th = \frac{\Delta K(L)_{th}}{\alpha\sqrt{(\pi(a + a0))}} \qquad (1)$$

$$a0 = \frac{1}{\pi}\left[\frac{\Delta K(L)_{th}}{\alpha\Delta\sigma_w}\right]^2 \qquad (2)$$

$$\Delta K(S)_{th} = \alpha\Delta\sigma_{th}\sqrt{(\pi a)} = \frac{\Delta K(L)_{th}\sqrt{a}}{\left[a + \frac{1}{\pi}\left[\frac{\Delta K(L)_{th}}{\alpha\Delta\sigma_w}\right]^2\right]^{1/2}} \qquad (3)$$

2.2 THRESHOLD CONDITION OF FATIGUE CRACK PROPAGATION DUE TO SMALL CRACK IN SPRING STEEL

In this paper we determined the fatigue limit of smooth materials ($\Delta\sigma_w/2$) and $\Delta K(L)_{th}$ of large crack to obtain the threshold condition of fatigue crack propagation due to small crack in spring steel using Haddad's formulae and taking the hardness and stress ratio into due consideration.

The results of the prediction of Shimizu et al.[8],as shown in Fig.1 , allow us to read as the formula (4) the hardness dependency of the true fatigue limit in high-strength, smooth materials. For the stress ratio dependency ($R=\sigma_{min}/\sigma_{max}=(\sigma_m-\sigma_a)/(\sigma_m+\sigma_a)$) of the fatigue limit in the fatigue limit $\sigma_{w,R=0}$ of the perfect pulsating stress (R=0)and that $\sigma_{w,R=-1}$ of the alternating stress (R=-1). Theformula (6) is therefore obtained in consideration of

$\sigma_a = -0.205\sigma_m + \sigma_{w,R=-1}$

and the fatigue limit which considers the hardness and stress ratio of smooth material can be determined by substituting the formula (4) into the (6).

$$\Delta\sigma_{w,R=-1}/2 = (1.73xHV - 3.39)/9.8 \quad (4)$$

where HV means Vickers hardness.

$$\Delta\sigma_{w,R=0}/2 = 0.83x\Delta\sigma_{w,R=-1}/2 \quad (5)$$

$$\Delta\sigma_{w,R=R}/2 = (1-R)x\Delta\sigma_{w,R=-1}/(1.205 - 0.795xR) \quad (6)$$

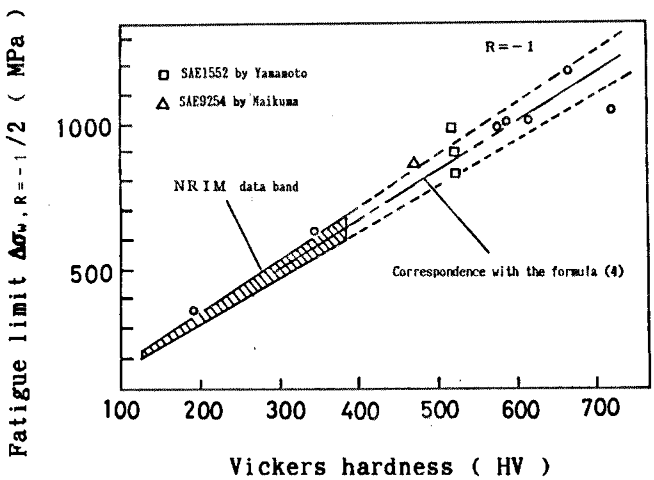

Fig.1. Relation between predicted fatigue limit of smooth material and hardness.[8]

The author [10] could establish the relationship between the fatigue crack propagation ratio (da/dN) of spring steel suffering large cracks with the stress ratio R=0 as shown in Fig.2 and the stress intensity factor range (ΔK), and then the formulate, as (7) and (8) the hardness dependency of $\Delta K(L)_{th}$ within the range of Paris' rule. Further the stress ratio dependency of $\Delta K(L)_{th}$ has been established by the formula (9) according to Luckas [11]. The value $\Delta K(L)_{th}$ for large cracks can be defined substituting formula (7) for (9) with the hardness and stress ratio taken into due account.

For G we decided the value G=0.75 though Usami [12] has reported G=0.8 for the range of stress ratio : $-5<R<0$.

$$\Delta K(L)_{th,R=0} = \begin{cases} -H + 66 & ; HRC >= 56 \\ 10 & ; HRC < 56 \end{cases} \quad (7)$$

$$da/dN = C \times \Delta K^{m} \quad (8)$$

$C = 2.018 \times 10^{-14} \times 1.195^{H}$

$m = -2.50 \times 10^{-2} \times H + 4.425$

Where H means Rockwell hardness.

$$\Delta K(L)_{th,R=R} = (1-R)^{G} \Delta K(L)_{th,R=0} \quad (9)$$

Substituting formulae (6) and (9) with Haddad's (1), (2) and (3) determines the threshold condition of fatigue crack propagation deriving from small cracks at different hardness and stress ratios. Fig. 3 shows a relationship between the crack length (a) and the critical stress amplitude ($\Delta\sigma_{th}/2$) where the crack starts to propagate under varied stress ratios. This is a case when a vertical stress is imposed onto the disk-shaped crack (radius: a) though the stress intensity factor range used here requires a calculation :

$$\Delta K = (2/\pi)\Delta\sigma\sqrt{(\pi a)}.$$

Fig, 4 represents the results of a comparison with the fatiguefracture datas [13] from non-metallic inclusion which is one of the representative small defects in order to verify the suitability of this consolidation method.

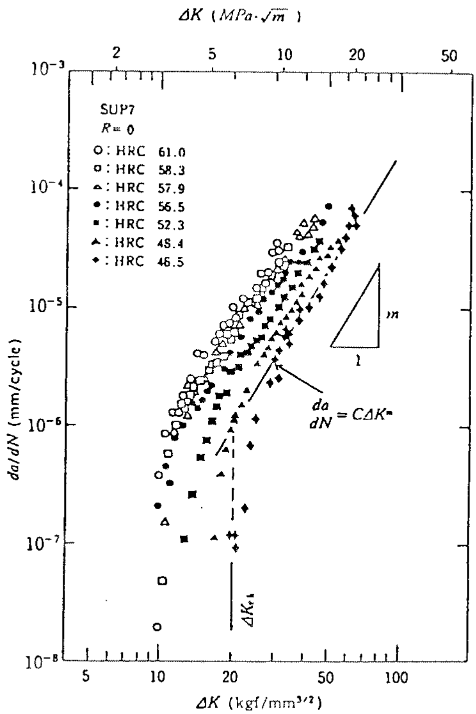

Fig.2. Property of large fatigue crack propagation on SUP7 [10]

The data result from a rotating bending fatigue test(R=-1) on the wire rod for springs with shot-peening applied later. In this case , an ellipsoid inclusion of 2a in major axis is regarded as a disk-shaped crack of 2a in diameter. Since the position of non-metallic inclusion is for the most part deeper than that when the compression residual stress is zero, it is conceivable that the influence of this stress is insignificant. From the figure it is clearly seen that the limit line of the fatigue fracture due to small cracks, as obtained in our consolidation method coincides well with the results of the fatigue fracture data forming the boundary of the lower limit . Our method enables therefore to define the threshold conditions of fatigue crack propagation of a spring steel having small cracks with the hardness and stress ratio dependency taken into account.

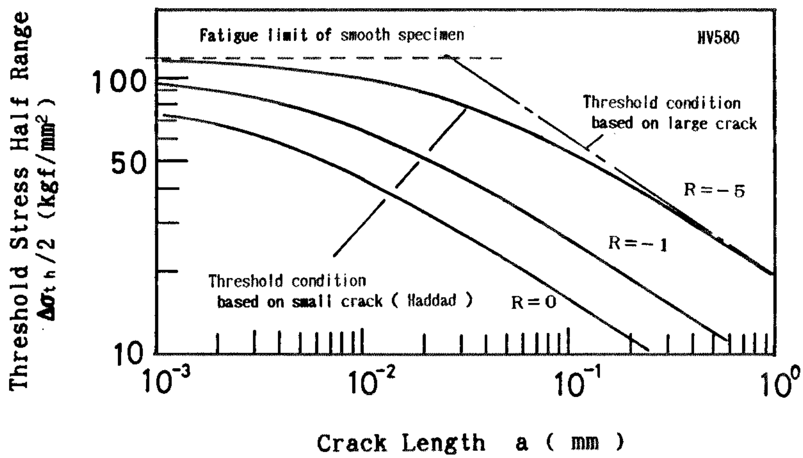

Fig.3. Relation between crack length and the predicted threshold stress range at R = 0 , -1 , -5.

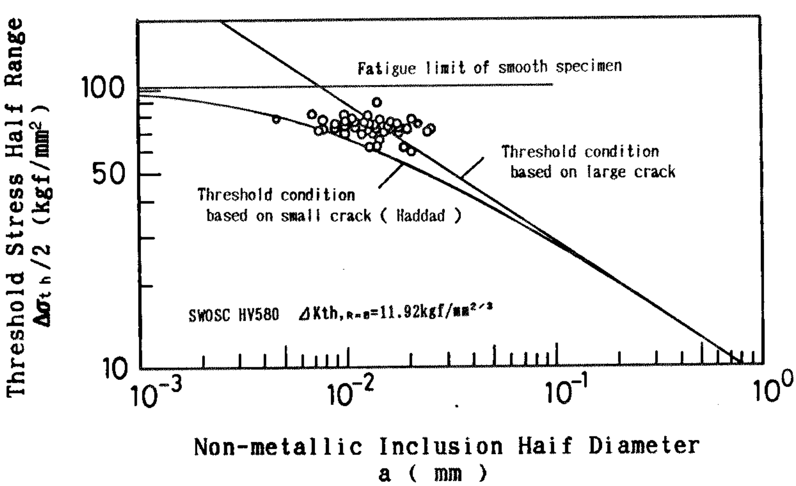

Fig.4. Comparison between the fatigue - fracture datas causing from non-metallic inclusion and the predicted threshold condition of small fatigue crack propagation.

3. INFLUENCE OF HARDNESS AND STRESS RATIO ON THE FATIGUE CRACK PROPAGATION RATIO OF SPRING STEEL HAVING SMALL CRACKS

Ohta [14] proposed formula (10) for a relationship in case of large cracks between the fatigue crack propagation ratio and stress intensity factor range with the stress ratio dependency taken into account.

Here formula (11) can be obtained if we use the value of small crack $\Delta K(S)_{th,R=R}$ as determined under Section 2.2 instead of $(1-R)^G \Delta K(L)_{th,R=0}$ in formula (10). As shown in Fig.5 , formula (11) implies that the property of fatigue crack propagation of large crack is extrapolated to the threshold condition of the small crack propagation. The fatigue crack propagation life can be obtained by numerical integration of formula (12) against the crack length.

$$da/dN = C(1-R)^{-mG}[\Delta K^m - \{(1-R)^G \Delta K(L)_{th,R=0}\}^m] \qquad (10)$$

$$da/dN = C(1-R)^{-mG}[\Delta K^m - \{\Delta K(S)_{th,R=R}\}^m] \qquad (11)$$

$$Nf = \int_{ai}^{af} \frac{da}{C(1-R)^{-mG}[\Delta K^m - \{\Delta K(S)_{th,R=R}\}^m]} \qquad (12)$$

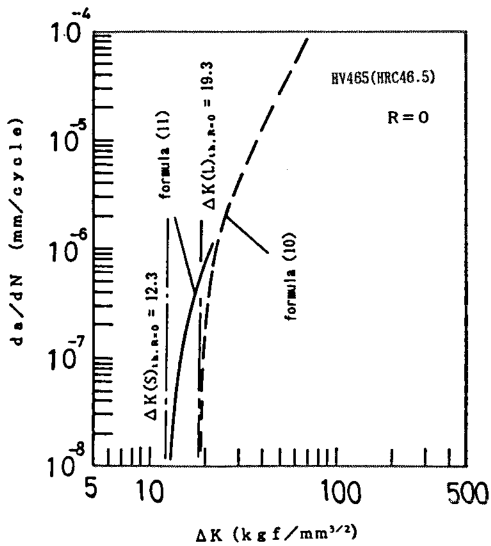

Fig.5. The assumed fatigue crack propagation property from small crack (a=0.01mm) and the predicted fatigue crack propagation property from large crack.

4. RELATIONSHIP BETWEEN RESIDUAL STRESS DISTRIBUTION AND FATIGUE CRACK PROPAGATION LIFE

The distribution of residual stress by shot peening takes various forms depending on the peening conditions (shot size, shot shape and shot-peening speed) and on the hardness of the material thus

shot-peened.
The representative forms are (1) when the surface residual stress is maximum, (2) when the inner residual stress is greater than the surface one, and (3) where the depth from the surface is great when stress is zero.
Fig. 6 illustrates the relationship between the number of cycles and length of propagation crack, obtained from formula (12) for suggested that the initial crack be semicircular, surface one (radius: 0.01mm) which is normal to the direction of bending stress. Strictly speaking the stress distribution is intricate where the residual stress overlaps external force and accordingly influence of stress gradient should be taken into account. The overlaped stress acting on the crack tip has however been assumed to act as a simple bending stress. We used formula (13) [15] for calculation of stress intensity factor.

$$\Delta K = 0.66 \times \Delta\sigma\sqrt{(\pi a)} \qquad (13)$$

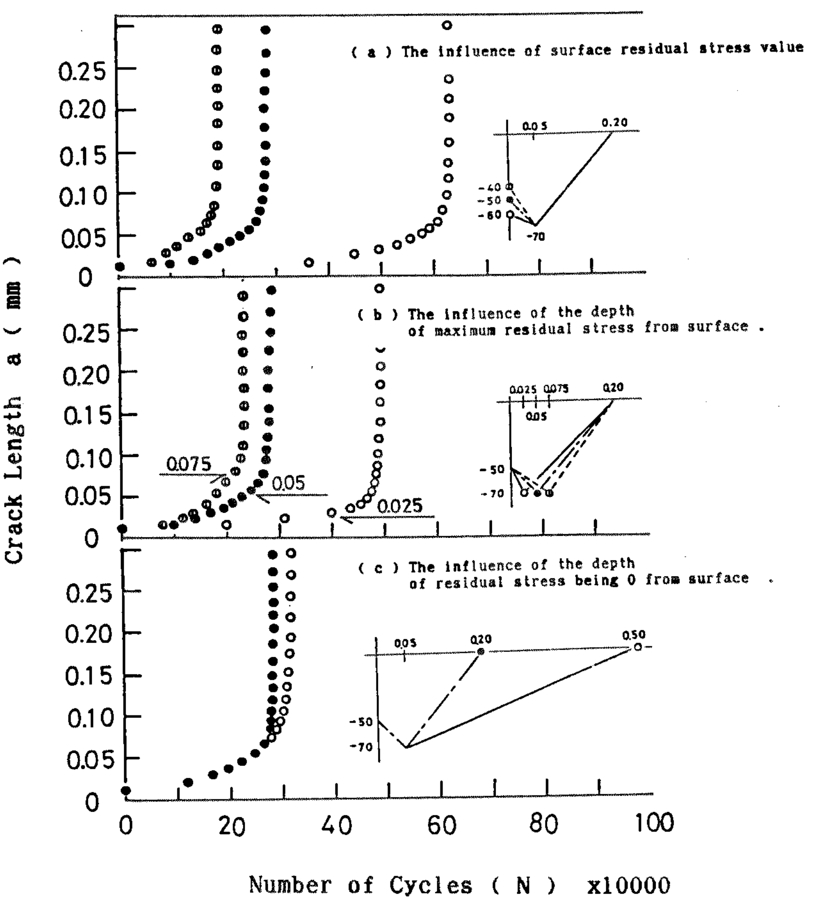

Fig.6. The influence of residual stress distribution pattern on the fatigue crack propagation behavior .
initial crack length (0.01mm) , R=-1

According to this Figure , the effects by residual stress distribution pattern on fatigue crack propagation are summarized as given below (1) the influence of the surface residual stress being extremely great, higher surface residual stress largely contributes to longer fatigue crack propagation life (Fig.6-(a)); (2) the nearer the position presenting the maximum value inside is to the surface, the longer fatigue crack propagation life is , and most of the propagation life is spent when the crack propagates to the position of the maximum residual stress (Fig.6-(b)) ; and (3) though the total propagation life is the longer, the deeper the position where the residual stress is zero, its contribution to the total propagation life is the smaller than result as (2) (Fig.6-(c)).

5. CORRESPONDENCE TO THE RESULTS OF ACTUAL FATIGUE TESTS

Fig.7 represents a comparison of our method with the results of actual fatigue test. Since in these test date the hardness and the distribution of residual stress as seen in Fig.8 are both different, this results in many differences in the fatigue life. Application of this method requires to know the geometrical shape and size of the initial crack. These value however, remaining unknown, we presumed a semi-circular crack whose radius is considered to be equivalent to the value of the maximum surface roughness of the shot-peened face. The distribution of residual stress used in our calculation is approximate to the actual one as shown by the thick lines in Fig.8.

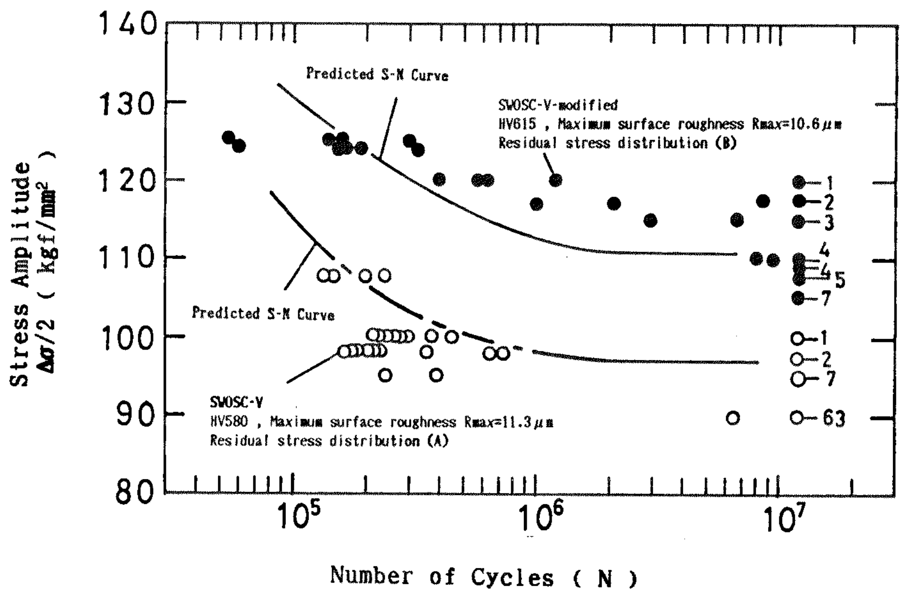

Fig.7. Comparision between the predicted S-N curves and the actual rotary bending fatigue fracture datas.

The S-N diagram we estimated involves a number of hypotheses. But both the fatigue limits and life approach the date obtained from experiments, which implies an effectiveness of our method.

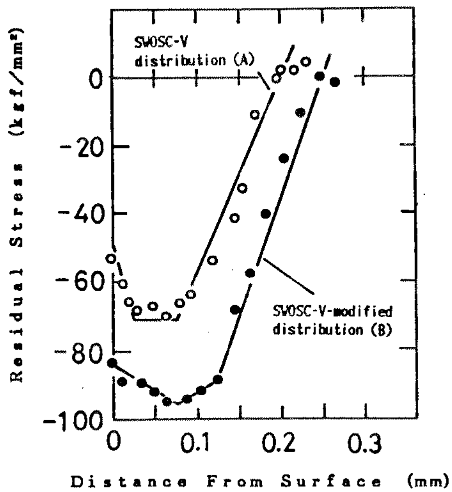

Fig.8. Residual stress distribution for use calculation. d=Φ4

6. CONCLUSIONS

(1) We propose, as the threshold conditions of small crack propagation in spring steel, Haddad's consolidation method where hardness and stress ratio dependency is considered.
(2) It is very important to raise the surface residual stress for enhancing the fatigue crack propagation life.
(3) Fatigue life is for the most part expended while the crack propagates from the surface up to where the compression residual stress is maximum.
(4) The nearer to the surface the position where the compressive residual stress is maximum, the longer life is extended.
(5) The predicted S-N curve by this method shows good correspondence with the actual results of the rotary bending fatigue tests.

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