Influence of Residual Stress on Fatigue Limit in Various Carbon Steels

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ABSTRACT

During cyclic loading, a high strength steel specimen consumes most of its life in the low crack growth rate region, which is characterized by transgranular slip decoherence and fine spacing striations. The residual stress distribution pattern in this region will greatly influence the fatigue behavior. In order to estimate the fatigue limit, an average value of residual stress in the low crack growth rate region is suggested. In taking this value into account the slope m of the straight line in the Goodman relation decreases with the increase of strength or hardness. A correlation is shown to exist between the static strength and fatigue limit.

KEYWORDS

Residual stress, fatigue limit, crack growth, Goodman relation, shot peening.

INTRODUCTION

Residual stress is an important factor influencing fatigue strength after shot peening. Most of the researchers concluded that the residual stress, σ_r, is equivalent in its effect to the mean stress σ_m. The fatigue limit increment, $\Delta\sigma_a$, follows the Goodman relation and can be expressed as

$$\Delta\sigma_a = -m(\sigma_r + \sigma_m) \qquad (1)$$

Here, m is a constant depending on the mechanical properties of the material. However, residual stress changes through the cross section while the mean stress is a constant value. It is yet uncertain how to cope with the various patterns of residual stress distribution. If an appropriate way of correlating residual stress distribution and fatigue limit is established, it would be beneficial to engineers for their practical applications. The present paper is focusing at this point, and trying to clarify the relation between m and the mechanical properties.

EXPERIMENTAL PROCEDURES

Three types of steel with different carbon contents namely, 20Cr(AISI 5120), 40Cr(AISI 5140) and GCr15(AISI 52100) were selected. The diameter of the round smooth specimen is 12mm. In order to keep the residual stress from relaxing, the specimens were quenched and low temperature tempered to reach a high strength level. All the specimens were ground. A number of specimens were shot peened. Some groups were polished after shot peening or grinding, so that their surface roughness are similar.

Fatigue tests were carried out in three point bending. The maximum alternating stress was determined as the fatigue limit when 60% of the specimens passed through $2x10^6$ cycles without failure.

Cr radiation and (211) peak were employed in x-ray stress measurement. Specimens which endured $2x10^6$ cycles at fatigue limit were subjucted to residual stress measurement. Stress distributions were brought about with etching. The final results have been corrected with the etched off depth.

Fracture surfaces were carefully observed. Various regions near the fatigue origin were examined according to the fracture characteristics.

RESULTS AND DISCUSSIONS

Three residual stress distribution curves of 40Cr specimens are shown in fig 1. No much difference are their surface or maximum values. How to find an appropriate residual stress value for fatigue strength estimation should be considered.

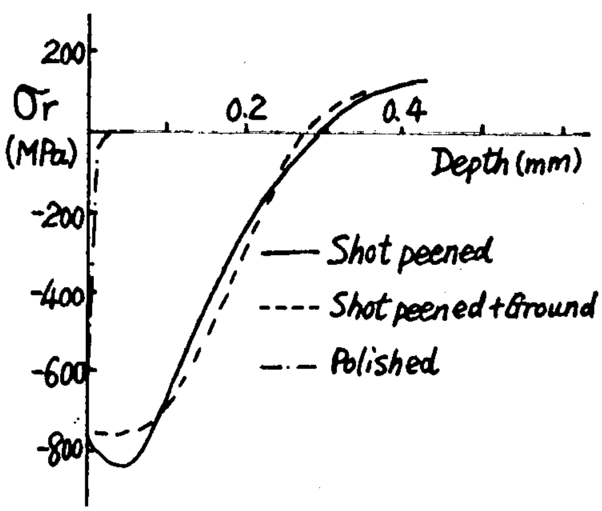


Fig.1 Residual stress distributions of 40Cr specimen

There were several ways to evaluate the effect of the residual stress.

a, Early work on a leaf spring took the maximum value of residual stress in the cross section as the mean stress, and a straight line appeared in the Goodman relationship

(Mattson,1960). However, both surface and subsurface crack initations were observed. Since the location of crack initiation does not agree with that of the maximum stress. Thus, the linear relation between the maximum stress and the fatigue limit seems to be unfavorable.

b, Residual stress right at the surface is widely employed in fatigue strength estimation when the crack initiates at the surface (Shozo,1977). In some materials, nevertheless, crack initiation is related to the hardness rather than the residual stress. In addition, the surface value won't influence a crack propagating a distance away from the surface. For instance, the residual stress value of a shot peened specimen right at the surface can eventually be identical to that of a ground one, but their fatigue strengths are quite different.

c, Xu et al (1981) suggested to use an area which is enveloped by the residual stress distribution curve from the surface to the peak. Good linearity was found between the size of this area and the fatigue strength. Since the effect of residual stress on crack propagation has been taken into account, it's thought to be better than to employ the surface value only. The problem is that the integral size of the area cannot be applied in the equation(1). Therefore, this correlation can merely be used in some specific specimens.

d, Starker(1981) took the local residual compressive stress as the mean stress to evaluate the local strength against fatigue failure. It is a good approach to estimate the fatigue crack initiating either on the surface or below the surface. But the correlation of residual stress and fatigue limit has not yet been established.

In order to find a better way of evaluating the effect of residual stress, it is necessary to correlate the residual stress with the fracture mechanisms. In fractographic investigations of hardened smooth specimens, a dark area can be easily examined in the peened specimen with low magnification (fig.2a). The fatigue origin is characterized by transgranular slip decoherence (fig.2b). Fig. 3a shows the appearence of transgranular fracture inspected with a replica. Fig 3b shows the striation next to the slip decoherence region. Normally, two types of striation can be observed in 40Cr specimen. Fine spacing striations are oriented randomly in smally patches, they are related to low crack growth rate. Once the striations are mainly perpendicular to the crack growth direction in coarse spacing, the stable crack growth rate stage starts. Thus, the low crack growth rate depth can be determined. Table 1 shows the depths of the three carbon content specimens. The size of the region is clear in both high and medium carbon hardened steels, while in low carbon steel it is somewhat less pronounced.

Basically, if a crack initiates at the surface, high strength smooth specimen would consume most of its life during cyclic loading in low crack growth rate region. Therefore, the residual stress magnitude and distribution in this region would be decisive for the fatigue behavior. In order to calculate the fatigue limit with the Goodman relation, it seems to be reasonable, as an approxmation, to take the average value of residual stress in this low crack growth rate region into account.

Since the specimen is subjected to cyclic bending load, it would be better to use the static bending strength σ_{bb} , instead of tensile strength σ_b , in plotting Goodman relation. For the 40Cr graund specimen four mean stress levels were applied namely, 0,800, 1300 and 1450MPa. The depth of the low crack growth rate region in ground specimen is about 60μm. The average residual stress value is -30 Mpa. The fatigue limits of ground specimens at different σ_m levels lie on a straight

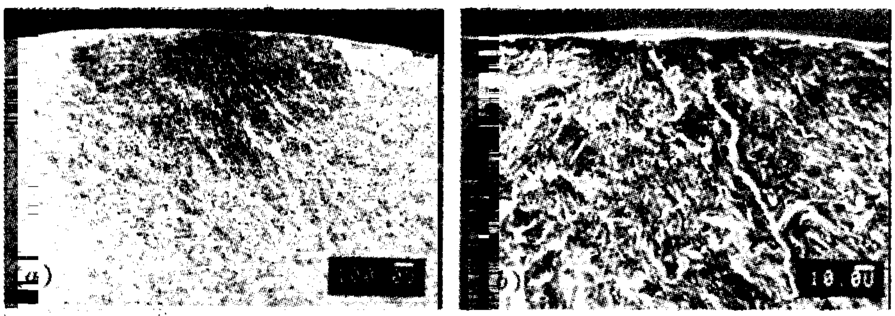


Fig.2 fracture surface on SEM

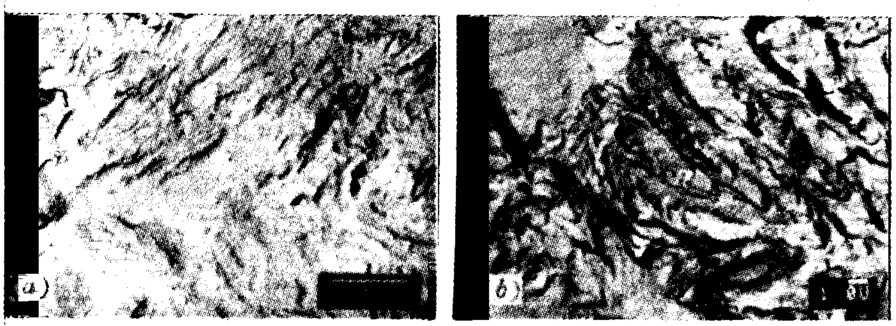


Fig.3 fracture surface replica on TEM

Table 1 Residual stress, transgranular crack depth and m value

	GCr15		40Cr		20Cr	
	G.	S.P.	G.	S.P.	G.	S.P.
Low crack growth rate depth (μm)	20	45	60	120	80	150
Average residual stress (MPa)	-40	-880	-30	-750	-500	-570
m value	0.10		0.15		0.18	

G.: Ground, S.P.: Shot Peened

line which passes through σ_{bb} with a slope of 0.15 (fig.4). The

σ_a value of shot peened-then-ground 40Cr stays above the straight line. Since its surface roughness is similar to that of the ground one, the extra increment of the fatigue limit is contributed by the other factors, such as the increase in hardness and the release of microstress. The difference of the shot peened-then-polished specimen to the shot peened one is due to surface topography.

The experimental data for 20Cr steel can also be treated in the same way. Its m equals 0.18. The m value of hardened GCr15 is 0.10 (Zhang, 1984).

Therefore, the contribution of the residual stress can be evaluated individually through this approach.

The relation of m and the mechanical properties can be evaluated by σ_a^0 VS. tensile strength, σ_b, curve, since m is used to be expressed in

$$m = \frac{\sigma_a^0}{\sigma_b}$$

Where σ_a^0 is the reverse bending fatigue limit at a certain number of cycles. The plot of σ_a^0 and σ_b is linear in the low σ_b range,

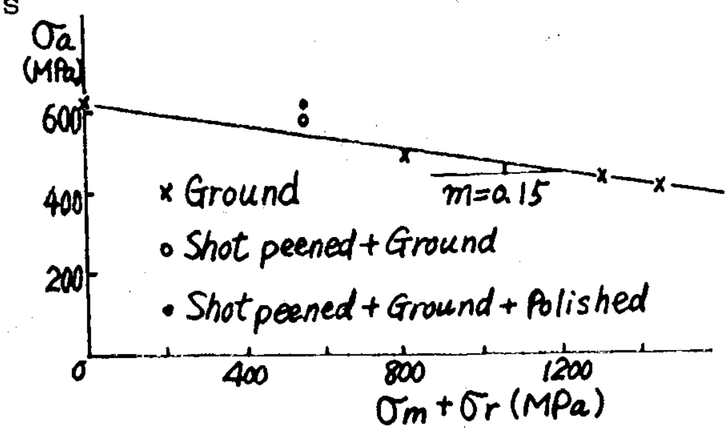
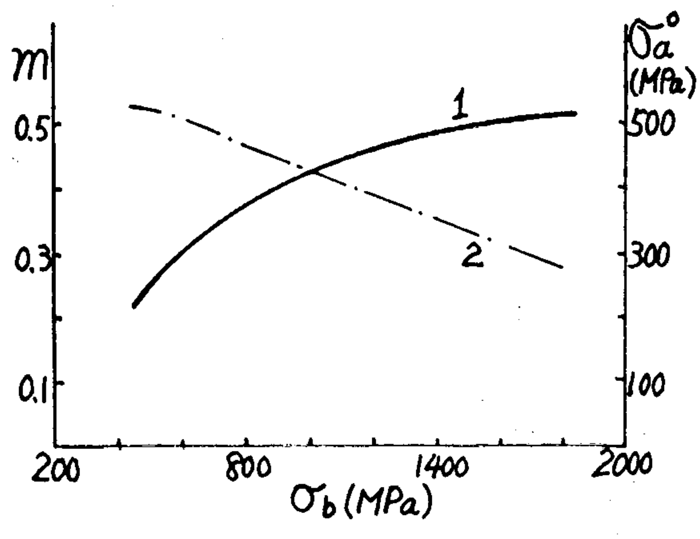


Fig.4 Goodman relation of 40Cr

but for high strength material, the curve flattens off, and even drops down due to the high sensitivity to surface quality and inclusions. The data of σ_a^0 and σ_b by Fuchs(1980) are expressed in curve 1 in fig.5. Naturally, the relation of m versus σ_b should appear as in curve 2. However, the m value presented in the literature indicated that m increases with the increase of σ_b or Hv(Koibuchi,1981,Starker,1981).

Fig.5 Correlation of m, fatigue strength and tensile strength



It is true that the higher the strength, the more significiant is the peening effect. But the contribution of residual stress should only be evaluated by m, if one agrees that the residual stress acts as mean stress. Therefore, the remaining contribution ought to belong to the other factors.

CONCLUSIONS

1. In fractographic examination of a shot peened specimen, a low crack growth rate region characterized by transgranular slip decoherence and fine spacing striation can be examined. For a high strength smooth specimen under cyclic loading, most of its life will be spent in the low crack growth rate region. Therefore, an average value of residual stress in this region is suggested to estimate the fatigue limit.

2. For a cyclic bending load, it is better to use static bending strength than tensile strength in the Goodman relation. Experimental results show that the slope m decrease with the increase of hardness or strength. A correlation exists between static strength and fatigue strength.

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