EFFECT OF BIAXIAL STRESS BY SHOT PEENING ON FATIGUE LIMIT

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ABSTRACT

Residual stresses are mostly created in a multiaxial state, even for thin layer surface hardening, it is yet biaxial. Dang–Van suggested a multiaxial fatigue criterion based upon maximum hydrostatic pressure P_{max} vs. cyclic shear stress τ_a. Shot peening and prestressed peening are applied in this study to adjust the residual stress values on the surface layers. σ_m is changed with different R ratios.Goodman and Dang–Van criteria are both employed to calculate the fatigue limit. Results show that the correlation coefficient of τ_a vs. P_{max} in the Dang–Van diagram is better than σ_a vs. $\sigma_m + \sigma_r$ in the Goodman diagram, due to the biaxial stress state of shot peened specimen. The way to characterize the residual stress and the evaluation of Dang–Van criterion are also discussed.

KEYWORDS

Residual stress, Shot peening, Fatigue limit

INTRODUCTION

Compressive residual stresses induced by shot peening are the major factor improving fatigue behavior. Usually, residual stress σ_r can be treated as mean stress σ_m and the Goodman relation is employed to evaluate its effect on the change of fatigue limit $\triangle\sigma_a$

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

m is a constant.

Care should be taken when the residual stress value is put into the equation (1), since residual stresses are varied through the cross section and the mean stress is constant. In term of uniaxial stress criterion, It's been suggested to use the average value of compressive residual stress in the low fatigue crack growth region for the fatigue limit evaluation [1]. It seems to be more appreciable than the surface or maximum residual stress value, since not only the magnitude of residual stress at a special point but its distribution at a distance will act on the short crack propagation and influence to the fatigue limit as well.

By the nature of residual stress, which should be built up in a three dimensional volume and balanced among different parts. Even for shot peening, the residual stresses are biaxial, thus a way of uniaxial stress evaluation is not appreciable. Being compared with various multiaxial criteria, Flavenot suggested to use Dang–van diagram in which cyclic shear stress τ_a is plotted against maximal hydrostatic pressure P_{max} and the three dimensional residual stress values are included in P_{max} [2].

Because of the initiation of a crack is resulted from shear of a crystallographic planes in a grain with a certain dimension, thus a better regression line should be obtained if a mean value of multiaxial stress over a depth from the surface was used. This depth of the critical layer depends on the material and is in between 40 to 180 μm as indicated in[3]. However, no relation has been found for the depth versus mechanical property of the material, the critical layer should be tested experimentally.

EXPERIMENTS AND RESULTS

Specimens were prepared with a medium carbon steel, and machined into 6 mm in diameter. Samples were oil quenched after 860℃ heating and 200℃ tempered. Its hardness is HRC 54–55. A part of specimens were peened with 0.5—0.8 mm diameter shots for 8 minutes. The Almen intensity was 0.42A (mm). Among them a group of specimens were peened under tension with a loading gadget, the tensile load was 200 MPa. Another part of specimens were rolled with a rolling force of 2 KN. In order to keep the fracture from the shoulders of the fatigue specimens, which were machined with an extra long holders, so both taper sides of the fatigue specimen can also be rolled. A group of specimens were rolled under tension with a loading force of 8 KN.

Reverse bending was carried out on a rotating fatigue machine with standard fatigue specimens. Three point bending with a mean stress was performed on high frequency electro–magnetic machine with smooth bar. The mean stress was fixed at 1360 MPa. The stress at which 50% specimens were survived after 10^7cycles is taken as the fatigue limit.

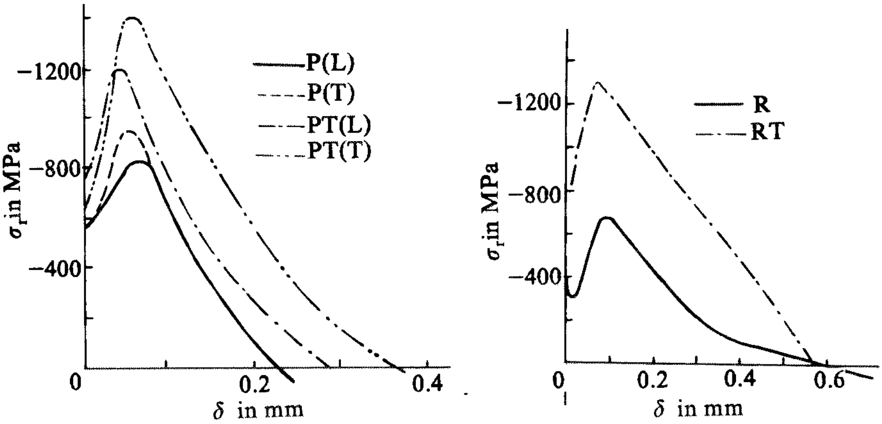
Residual stress was measured on the Rigaku MSF–2M stress analyzer with $\sin^2\psi$ method. Cr–Kα was employed and (211) diffraction of α–Fe was recorded. Fractography was studied with scanning electron microscope.

Results of fatigue limit testing are listed in Tab.1

Tab.1 Fatigue limits for different states of quenched medium carbon steel

Sample states	Fatigue limit(MPa)	
	Reverse bending σ_{-1}	Three point bending σ_a (σ_m = 1360)
Ground (G)	620	–––
Shot peend (P)	730	520
Peened under tension (PT)	–––	620
Rolled (R)	820	–––
Rolled under tension (RT)	830	–––

Fig.1a shows the longitudinal and tangential residual stress distributions of the states of peened (p) and peened under tension (PT) specimens. The magnitude and depth of compressive residual stresses in the surface layer of PT specimen are greater than that of P specimen and the tangential stress is higher than the longitudinal stress. Under three point bending with a mean stress, compressive residual stress decayed for PT specimen and its peak value beneath the surface relaxed more than the surface value. The compressive residual stress does not change much after the testing at the fatigue limit stress level of P group specimen.



(a) (b)

Fig.1 Residual stress distribution of (a) shot peened (b) rolled

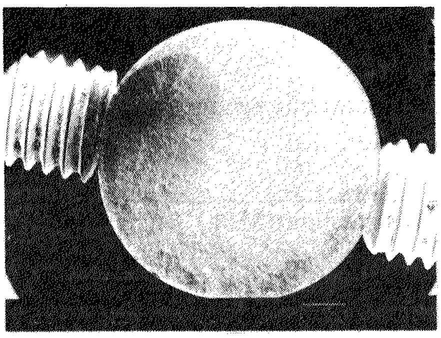


Fig.2 Subsurface crack origin of rolled specimen

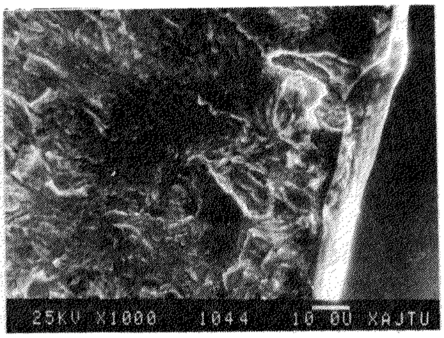


Fig.3 Surface crack origin of peened speimen

Tab.2 Fractography of fatigue fracture

Loading	Sample state	Crack Initiation		Low crack growth rate region size(μm)
		Site	Depth	
Reverse bending	G	Scratch	Surface	60
	P	Inclusion	Subsurface	——
	R	Inclusion	Subsurface	——
	RT	Inclusion	Subsurface	——
Three point bending	P	Peening pitch	Surface	90–100
	PT	Peening pitch	Surface	90–100

Fig.1b shows the longitudinal residual stress distributions through the depths of R and RT specimens and the compressive residual stress are higher for the RT states too. The features of fractography are shown in Tab.2. The size of the low crack growth rate region was measured with scanning or transmission electron microscope and was characterized with slip decoherence. Fig.2 shows the fatigue nucleation area at the subsurface region of rolled specimen. The fatigue origin for the three point bending at the surface of the shot peened specimen is shown in Fig.3.

DISCUSSIONS

Evaluation of Residual Stress on Fatigue Limit by Dang–Van Criterion.

Multiaxial stresses in Dang–Van plot are included in the maximal hydrostatic pressure Pmax, which is the summation of average maximal values in the three directions.

$$P_{max} = 1/3\,(\sigma_{1max} + \sigma_{2max} + \sigma_{3max}) \qquad (2)$$

and

$$\sigma_{max} = \sigma_a + \sigma_m + \sigma_r \qquad (3)$$

The average values of the compressive residual stress in the low crack growth rate region are listed in Tab.2. Loading stress σ_a varies only slightly in the depth of low crack growth rate, its surface value is employed for Pmax determination. Tab.3 presents the data for Dang–Van plotting, σ_r^L and σ_r^T are the residual stress in the longitudinal and tangential directions.

Tab.3 Data for Dang–Van plotting in MPa

No.	Sample state	σ_r^L	σ_r^T	σ_m	σ_a	τ_a	P_{max}
1	G	−30	−30	0	620	310	190
2	P	−700	−700	0	730	365	−223
3	R	−600	−600	0	820	410	−127
4	RT	−800	−800	0	830	415	−260
5	P	−700	−700	1360	520	260	160
6	PT	−930	−1010	1360	620	310	13
7	G	−30	−30	800	490	245	410
8	G	−30	−30	1300	440	220	560

For comparison, the Goodman and Dang–van plots is shown in Fig.4 and 5. Numbers in the two plots stand for the sample code in Tab. 3. As a check of the Dang––Van plot, the data of fatigue tests with different mean stresses for ground specimens No. 1,7 and 8 were put on both plots. The slopes in the Goodman and Dang–Van relations are −0.15 and −0.27 respectively. The correlation coefficients are both equal to 0.999. Therefore, Dang–Van diagram is as good as the well accepted Goodman relation for the evaluation of the effect of uniaxial mean stress on the fatigue limit.

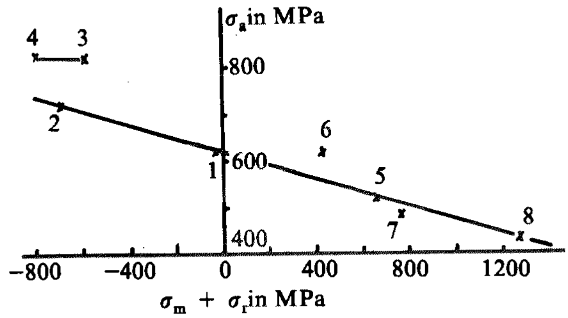


Fig.4 Goodman plot

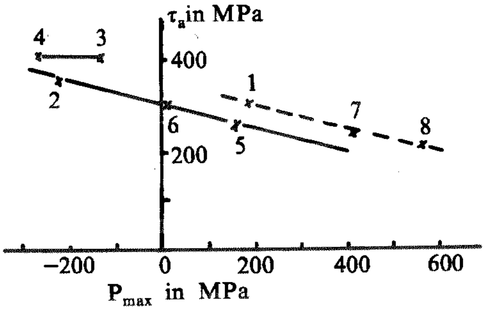


Fig.5 Dang–Van plot

Peening intensities of No. 2.5 and 6 are equal. The residual stress value of No.5 is the same as No.2 but their mean stresses are different. For No.5 and No.6, their mean stresses are equal and residual stresses are different. If a regression line is drawn with No.2.5 and 6, the results are listed in Tab.4. In fact, the slopes of No.2 and No.5 are the effects of mean stresses on fatigue limits and the slopes of No.5 and No.6 are the effects of residual stresses on fatigue limits. No.2,5 and 6 on the same line in the Dang–Van plot indicates that biaxial residual stress state should be taken into account if residual stress is calculated as mean stress. In other words, if uniaxial residual stress only is evaluated, the fatigue limit increaes more than it should be as No.6 in the Goodman plot.

Tab.4 Regression parameter for Goodman and Dang––Van plots

Regression	*Slope*	Correlation Coefficient
Goodman	−0.15	0.943
Dang–Van	−0.24	0.994

In the Dang–Van plot, the regression line of shot peened samples is basically parallel to that of ground sample but lower. The factors other than residual stress such as surface roughness cause the difference, since the hardened specimens are sensitive to the surface roughness on the fatigue behavior, therefore the fatigue limits of shot peened group drop more than the rolled one.

Estimation of Residual Stress on Fatigue Limit associated with the Location of Fatigue Origin.

The compressive residual stress of rolled under tension (No.4) is much higher than the rolled No.3, but their fatigue limits are close,that is quite different from the peened one. For No.3 and No.4 the subsurface fatigue origins are located at a depth of 0.6—0.8 mm from the surface, thus the difference of compressive residual stresses in the surface layer does not make great difference on fatigue limit.

In addition, It is hard to define the low crack growth rate region for suburface crack, the residual stress value cannot be determined by the method mentioned. The tested data can neither fit in Dang–Van plot or in Goodman relation as No.3 and No.4 in Fig.4 and 5. This fact may lead a conclusion that the Dang–Van plot is only good for that the fatigue crack initiates at the surface. If the mean stress is increased in the three point bending to force the fatigue crack initiating at the very surface, the fatigue limit of No.5 and No.6 will be placed in a straight line with a slope of 0.15 which is equal to the slope for ground specimens with different mean stresses.

Discussion about Dang–Van Relation

The Dang–Van relation can be expresses in

$$\tau_a + \alpha P_{max} = \beta \qquad (4)$$

α and β are constants.

The cyclic loading stress is both included in τ_a and Pmax. but is separated in the normal stress and shear stress as the two axises. For smooth specimen the fatigue limit basically depends on the duration of crack initiation and the shear stress should be the driving force. so it is appropriate for tension, bending and torsion fatigue limit evaluations. The factor of 1 / 3 in Eq.2 only changes the value and the slope of regression line in the Dang–Van plot. It makes no substantial effect on the role of residual stress. β in Eq.4 is the fatigue limit of reverse torsion with no residual stress involved. For bending, τ_a equals to $\frac{1}{2}\sigma_a$, $\sigma_a$is the cyclic stress amplitude. α is the slope depending on the strength of the material.

CONCLUSIONS

Residual stress by its nature should be three dimensional, even for surface mechanical treatment, it is biaxial. If the residual stress is treated as a mean stress to evaluate its contribution on fatigue behavior, the residual stress is not appreciable to be taken as a uniaxial stress value. Since hydrostatic pressure is involved in the Dang–Van relation, which is better than the Goodman relation.

The average value of compressive residual stress in the depth of low crack growth rate region under the loading level of fatigue limit is good for the assesment of the role of residual stress by Dang–Van relation. Good linear regressions are found for the different mean stresses and different residual stresses in the Dang–Van plot. Their slopes are very close showing that once the residual stress value is taken properly the residual stress can be treated as a mean stress.

Dang–Van relation is true when the fatigue crack initiates at the very surface. If the fatigue origin lies beneath the surface, the role of compressive residual stress decreases, the Dang–Van relation fits no longer.

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