THE EFFECT OF SURFACE PLASTIC DEFORMATION ON FATIGUE STRENGTH AND ITS MECHANISM

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ABSTRACT

The effect of shot peening and surface rolling on fatigue strength of a medium carbon chromium steel at different heat treated conditions was investigated and emphatically discussed from the changes in residual stresses, structure and fractographic morphology.

KEYWORDS

Surface plastic deformation; fatigue strength; residual stresses; structrual and fractographic changes.

INTRODUCTION

It is well known that the fatigue strength of parts and specimens are enhanced by shot peening or surface rolling and critically discussed by many investigators (Almen, 1963; Starker, 1979; Balter, 1978; Ho, 1979).The application of surface rolling is limited to cylindrical parts but shot peening can be used for various shapes. Some authors (Starker,1979; Balter, 1978) considered that macroscopic residual stress is the major factor affecting the fatigue strength, and the quantitative correlation between bending fatigue strength and longitudinal residual stresses can be expressed by formulae. Bahre (1978) found that the work hardening is a major factor for smooth specimen. Balter (1978) thought that the microscopic homogeneity of martensite in hardened steel is an important factor for increasing the fatigue strength. On the other hand, the effect of work hardening was always judged by means of increment in hardness. Syren (1976) found that work hardening is consistant with microscopic residual stresses.

In order to further investigate the effect of surface plastic deformation on fatigue strength, experiments were performed on a medium carbon chromium steel (45Cr) of two heat treated conditions. The relation of fatigue strength, residual stresses structural and fractographic changes after shot peening or surface rolling are discussed.

EXPERIMENTAL

The steel (45Cr) has a chemical compositions of 0.46%C, 0.26%Si,0.66% Mn, 1.11%Cr, 0.014%P, 0.008%S. Initially oversized blanks (Φ10.7X100mm) cut from not rolled bars were austenized in a solt bath for 10 minutes 860°C, quenched in oil and tempered for 2 hours at 200°C or 600°C respectively. The former is tempered martensite with high strength. The latter is the mixture of carbide and recrystallized ferrite with low strength and high plasticity. The dislocation arraies of the two states are totally different (Zhou, 1980).

After heat treatment, the specimens were ground down to the final dimensions (Φ10X100mm). Then, the following two methods of surface plastic deformation were applied to the specimens. 1) shot peening, shot dia.: 0.5mm, Almen intensity: 0.50B (tempered at 200°C) and 2) surface rolling, rolling force: 600kgf (tempered at 200°C) ; 50kgf and 200 kgf (tempered at 600°C).

Asymmetrical cyclic three points bending fatigue tests were carried out on a high frequency fatigue testing machine, holding the minimum stress values constant. To change the degree of attenuation of residual stresses during the fatigue test, σmin=22 and 89kgf/mm² were chosen respectively. The max. stress amplitudes which will endure 2X10⁶ cycles were taken as fatigue limit. Using X-ray stress analyzer, the macroscopic residual stresses (σ_r) in the specimens were determined selecting CrK_α(211) interference lines and the half-value breadths (B) of the interference profiles in incident angle 0° were also measured. Vicker hardness were determined along the transverse section of specimens after strengthening. The fracture morphology and characteristics were observed by electron microscope.

EXPERIMENTAL RESULTS AND DISCUSSION

Residual stress distribution and the changes of half-value breadth of specimens after shot peening and surface rolling can be seen from Fig.1. It is worth notice that specimens tempered at 200°C after surface plastic deformation differ from that at 600°C on change tendencies of B. The former is decreasing and the latter increasing. The measurement of hardness shows that the micro-hardness value of specimens in the surface plastic deformation layer are both raised. Table 1 summarizes the resulting data of tests.

Comparing the fatigue limit of surface rolled specimens with different σmin., i.e. different mean stress, with the increase of σmin, i.e. working stress, the attenuation of residual stresses is also increased, and in consequence the fatigue limit is lowered correspondingly, in extreme case even lowered to below the virgin fatigue limit. This strongly suggests that the affect of residual compressive stress on the fatigue strength of surface plastically deformed material is very pronounced.

The fatigue strength of specimens tempered at 200°C is raised appreciably by both shot peening and surface rolling. By comparision of the surface finish, residual stresses and fatigue limit of the specimens after shot peening and surface rolling, it is seen that fatigue properties of specimens after surface rolling are better than that after shot peening. This is due to the fact that the residual compressive stresses formed by shot peening are lower, depth of strengthen layer is

TABLE 1 Resulting Data of Tests

State of specimens	Roughness R_z (μm)	Hardness H_V	σ_r before fatigue		σ_r after fatigue at σ_w				Fatigue limit			
					$\sigma_{min}=22$ kgf/mm²		$\sigma_{min}=89$ kgf/mm²		$\sigma_{min}=22$ kgf/mm²		$\sigma_{min}=89$ kgf/mm²	
			$\sigma_{r\,max}$ (kgf/mm²)	Depth of layer (mm)	$\sigma_{r\,max}$ (kgf/mm²)	$\Delta\sigma_{r\,max}$ (%)	$\sigma_{r\,max}$ (kgf/mm²)	$\Delta\sigma_{r\,max}$ (%)	σ_w (kgf/mm²)	$\Delta\sigma_w$ (%)	σ_w (kgf/mm²)	$\Delta\sigma_w$ (%)
200°C tempered	1.65	526	-50	0.01	-57	+14	-60	+20	185	-	250	-
200°C tempered & shot peened	8.87	600	-100	0.25	-99	0	-	-	195	5.4	-	-
200°C tempered & 600kgf rolled	0.12	580	-200	1.30	-167	-16	-155	-23	250	35	310	24
600°C tempered	1.95	265	-37	0.02	-40	+8	-46	+24	135	-	190	-
600°C tempered & 50kgf rolled	0.23	280	-82	0.50	-60	-27	-48	-41	150	11	195	2.6
600°C tempered & 200kgf rolled	0.75	295	-87	1.10	-57	-34	-42	-52	160	19	180	-5

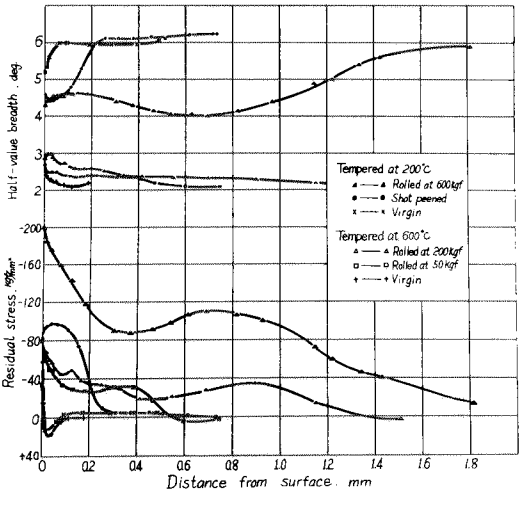

Fig. 1. Residual stress distribution and the changes of half-value breadth.

shallower, especially the surface finish become more rough. Of course this is the case when we have only used one set of shot peening parameter which is suitable to small parts. The fatigue limit of specimens tempered at 600 °C when polished so as to make the surface finish same as those surface rolled, was raised from 135kgf/mm² to 140kgf/mm² ($\Delta\sigma_w$ =3.7%) in the case of σ_{min} 22kgf/mm² . Therefore, the effect of surface finish on fatigue strength can not be neglected. In what follows, in order to simplify the problem, we will discuss the effect of residual stresses and microstructural and fractographic changes on fatigue strength after surface rolling, neglecting the effect of surface roughness.

In the case of specimens tempered at 600 °C, with increasing rolling forces, fatigue limit was raised with σ_{min} of 22kgf/mm² , but with σ_{min} of 89kgf/mm² , fatigue limit of specimens after rolled at 200kgf was even lower than that before rolling, and fatigue limit of specimens rolled at 50kgf still raised a little. The difference lies apparently on the different degree of attenuation of the residual stresses due to difference in the applied mean stress. As to the changes in the state of dislocation structure reflected by the half-value breadths and that of surface hardness of specimens rolled at 200kgf were much larger than that rolled at 50kgf. Apparently this difference can no longer be attributed to the difference in residual stresses.

TEM observations indicated that considerable plastic deformation caused carbide particles appear in directionary arrangements in the soft ferrite matrix of surface layer of the specimen after rolling at 200kgf as shown in Fig.2a. The dislocation density of phase boundary between the carbide and ferrite near surface is higher than that on the inner layer, because of inhomogeneous plastic deformation. Even some microcrack may be formed at that location. We may think of these as a damage of phase boundaries. Figure 2b, 2c show that there are many steps and even secondary cracks near the fatigue origin region on the fracture surface and their direction is same as the trace in direction formed by plastic deformation. As mentioned above, this characteristic also appears in specimens rolled at 50kgf, but much lighter. This shows that for specimens tempered at 600 °C after surface plastic deformation not only strengthening but also damage happen their degree being relevant to the strengthening parameter. Therefore, it is not sufficiant to express the structural changes and its influence only by the changes in hardness of specimens.

It follows that, the effect of plastic deformation on structural changes of specimens tempered at 600 °C on fatigue strength contain two contrary aspects, i.e. strengthening and damage. Therefore the effect of structural changes is small by comparision with residual stresses. The fatigue limit of specimen rolled at 200kgf is higher than 50kgf, when σ_{min} is 22kgf/mm² , because the former has a higher residual compressive stresses which overcome the harmful action caused by the damage. however, if residual stresses are attenuated appreciably, structural changes become the main factor affecting fatigue strength. For this reason, the fatigue limit of specimens rolled at 50kgf is better than that rolled at 200kgf when σ_{min} is 89kgf/mm² . Damage can also occur in materials of low strength, when shot peening intensity is too high, resulting in over peening.

As mentioned above, after shot peening or surface rolling, the hardness of specimens tempered at 200 °C was increased, but half value breadth was decreased. As a rule, half-value breadth of diffraction

profile depend upon microscopic residual stress and dislocation structure. As it is known that the heterogeneity of substructure of low tempered martensite is rather high and there may exist microscopic residual stress peaks so the half value breadth is usually large. The half value breadth should have been further raised after shot peening or surface rolling due to the modification of dislocation cell structure. But it is probable that plastic deformation has, to some extent, relaxed local microstress peaks because deformed compressive stresses acted on specimens repeatly. When the latter effect exceeds the former, the half value breadth is lessened. This process signifies the overcoming of weak links in micro-regions in the tempered martensite, therefore the mechanical properties of the material are improved. Static bend tests show that specimens after rolling not only posses a higher bending strength but also a larger deflection as shown in Table 2. Electron microscope observation indicates that there are about 10-20% intergranular fracture and some secondary cracks besides cyclic cleavage near the origin of fatigue in specimens which are not rolled as shown in Fig. 2d. After rolling, the surrounding region near the fatigue origin appears to be all cyclic cleavage. Intergranular fracture and secondary cracks can be discovered only when the crack has propagated to a certain depth.

TABLE 2 Static Bending Properties of Specimens

States of specimens	Bending yield strength σ_{sb}, kgf/mm²	Bending strength σ_{bb}, kgf/mm²	Deflection f, mm
200 °C tempered	226	490	4.0
200 °C tempered 600kgf rolled	241	498	4.6

Besides, for specimens tempered at 200 °C, the location of fatigue origin on the fracture surface after surface rolling are relevant to the applied stress. When the applied stress is lower (σ_{min}=22kgf/mm², $\sigma_{max} \leq$270 kgf/mm²), fatigue nucleus may be shifted to the subsurface (1mm below the surface) forming a "fish eye". The position of the fatigue origin corresponds to the layer thickness of residual compressive stress. The center of the fish eye is a non-metallic inclusion. The crack propagation toward the surface is quite slow, even though the applied stress on the surface layer is high. Since the residual compressive stress retards the crack propagaion , so that flat and smooth regions in the fracture were observed by SEM, its colour was quite dark.

Therefore, the improvement in fatigue strength of specimens tempered at 200 °C after surface plastic deformation is the over-all effect of macroscopic residual compressive stress, surface finish and structural changes. Among these residual stress plays a major role. This is due to the fact that higher residual stress values and deeper strengthening layer can be obtained by surface plastic deformation and much less attenuation of residual stress results during cyclic loading. At the same time the fatigue origin can be shifted to subsurface. On the other hand, beneficial changes in the substructure, increase in surface hardness and relaxation of local microscopic stress peaks all pool into the fatigue strength improvement. Obviously if the effect of structural changes be neglected, it may lead to over estimate the effect of residual stress, when we try to establish a relation between fatigue limit and residual stresses and it is also unfair to characterize structural changes only by hardness changes. Through the above discussion, we may

once again clarify why surface plastic deformation produces very beneficial strengthening effect under high cycle fatigue loading, for specimens tempered at low temperature such as 200 °C.

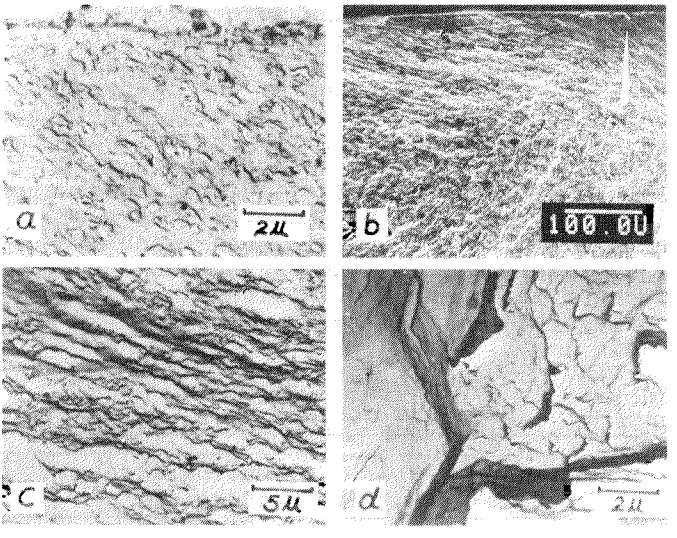

Fig. 2. Electron microscope photograph.
a) 600 °C tempered and rolled.
b) 600 °C tempered, rolled and fatigued. (the origin is pointed by the arrow)
c) 600 °C tempered, rolled and fatigued near origin.
d) 200 °C tempered virgin near origin.

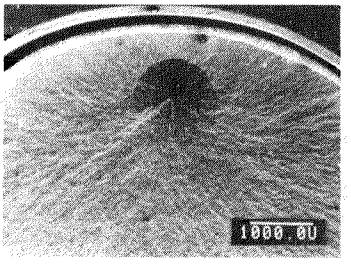

Fig. 3. Fish eye fatigue region.

CONCLUSIONS

1. The improvement of fatigue strength by surface plastic deformation can be attributed to three fundamental factors: macroscopic residual stress, surface finish and structural changes. The effect of these fundamental factors on fatigue strength varies with original structure, strengthening method and applied stress.

2. For specimens tempered at 600 °C after surface plastic deformation, structural changes may not only result in work hardening but also structural damage. Their effect on fatigue strength is generally smaller than that of residual stress. But it can also become a main factor affecting fatigue strength, when residual stress be attenuated appreciably.

3. For specimens tempered at 200 °C, surface plastic deformation produces very beneficial strengthening effect. Besides residual compressive stress, the improvement of micro-homogeneity of tempered martensite, which brings about more favorable substructural conditions also plays an important role for its resistance against fatigue.

4. The hardness of specimens always increase after surface plastic deformation, but different structural changes occur in materials with different original structure, so that their effect on fatigue strength is diffenent. Therefore, it is insufficiant to express the structural changes and its effect on fatigue strength only by changes in surface hardness.

REFERENCES

Almen, J. O. and P. H. Black (1963). Residual Stresses and Fatigue in Metal. McGraw-Hill, New York.

Bahre, K. (1978). Zeitschrift für Werkstofftechnik, 9, 45.

Balter, M.A. (1978). Strengthening of Machine Parts, Machine Building, Moscow.

Ho, J. W. and Zhang, D. Q. (1979). Effect of Residual Stresses Produced by Heat Treatment and Surface Cold Working on Mechanical Properties of Steels. Research Report, Res. Inst. Strength of Metals, Xian Jiaotong Univ. P.R. China.

Starker, P., H. Wohlfahrt and E. Macherauch (1979). Fatigue of Engineering Materials and Structures, 1, 319.

Syren, B., H. Wohlfahrt and E. Macherauch. (1976). Proceedings of the Second International Conference on Mechanical Behavior of Materials, Boston, Massachusetts, U.S.A.

Zhou, H. J. (1980). Proceedings of the 18th International Conference on Heat Treatment of Materials, Detroit, Michigan, U.S.A. 263-276