Influence of the Change of Microstructure and Residual Stress Field in the Surface Shot-Peening Straining Layer on Fatigue Behavior

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Introduction

The microstructure and the residual compressive stress field in the surface shot-peening straining layer are two strengthening factors for improving the fatigue behavior of materials. It was shown that the monotonic yield strength of materials is the main factor effecting the fatigue behavior (1). But the further study shows that there is a difference between the monotonic yield strength and the cyclic yield strength of materials and the monotonic mechanical property of materials can not represent the slipping property of crystals under the alternating stresses. In shot peening process, the cyclic strain produces in the surface layer (2,3) and therefore the cyclic hardening/softening in the surface layer would occur, resulting in the change of cyclic property of material. The relationship between the cyclic property and the fatigue behavior of materials has been investigated in this paper. Moreover, the residual stress field (RSF) induced by shot peening (SP) can relax during fatigue. The relaxation of RSF could be divided into the static load relaxation (SLR) at the initial fatigue stage and the dynamic load relaxation (DLR) at the medium and last fatigue stage. The damage of material in the surface layer caused by SLR and the harmful effect of the damage on the fatigue behavior has been investigated also. To avoid SLR, the optimum RSF is discussed.

Material and machnical properties

The test material used was a superhigh strength steel GC-4 (0.4C-1.43Si-1.73Cr-1.2Mn-0.5Mo-0.08V). Two heat treatments were used (see Tab. 1) to obtain the specimens with different cyclic property in the case of having similar tensile strengths. The mechanical properties is listed in Tab. 2.

Tab. 1 Heat treatment

Specimen	Heat treating regime
A	920°C, heating→190°C, isothermal quenching for 1 h in salt bath, cooling in air→260°C, tempering for 4 h, cooling in air
B	920°C, heating→310°C, isothermal quenching for 9 min, cooling in oil→220°C, tempering for 4 h, cooling in air

Results and discussion

1. Relationship between the cyclic property and the fatigue behavior of material

(1) SP is a cyclic strain process

Tab. 2 Mechanical properties

Specimen	Monotonic tensile strength σ_b, MPa	Monotonic yield strength $\sigma_{0.2}$, MPa	Cyclic yield strength $\sigma'_{0.2}$, MPa	Monotonic strain hardening exponent n	Cyclic strain hardening exponent n'
A	1949.4	1564.6	1350.0	0.15	0.13
B	1916.8	1185.2	1460.0	0.25	0.09

The monotonic and the cyclic stress-strain curves of two group of A and B specimens are shown in Fig. 1. Under the similar tensile strength, A and B specimens show the cyclic softening and the cyclic hardening property respectively.

It has been found that after SP the maximum compressive stresses in RSF of A specimens are far lower than its monotonic $\sigma_{0.2}$, while that of B specimens are far higher than its monotonic $\sigma_{0.2}$ (see Fig. 2). This phenomenon shows that the materials in the surface layer of A specimen experience the cyclic softening and the materials in the surface layer of B specimen experience the cyclic hardening. To confirm above results, SP for two side of specimens with thick of 1 mm was performed. The test results are listed in Tab. 3. It is shown that after SP the cyclic softening results in the decrease of $\sigma_{0.2}$ (A specimen), but the cyclic hardening results in the increase of $\sigma_{0.2}$ (B specimen). It can be concluded that SP is a process of cyclic plastic strain in the surface layer.

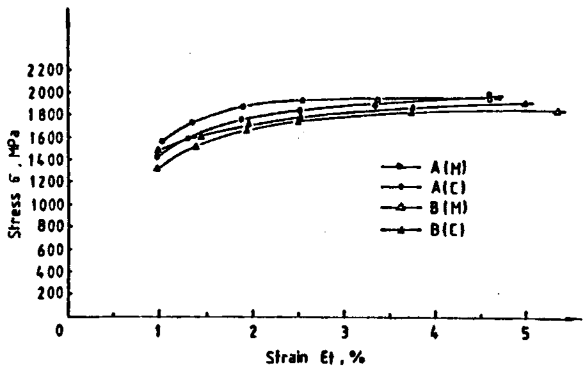


Fig. 1: Monotonic (M) and cyclic (C) stress-strain curves

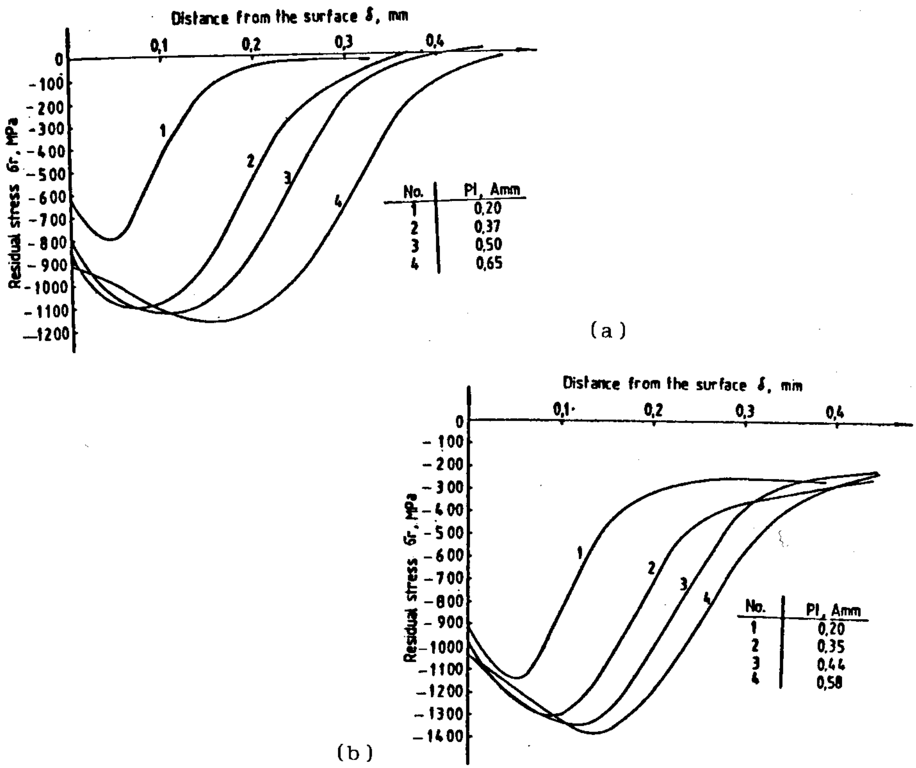


Fig. 2: RSF induced by SP (PI-peening intensity)

Tab. 3 Yield strength of peened and unpeened specimens

Specimen	Yield strength $\sigma_{0.2}$, MPa	
	unpeened	peened
A	1373.0	1301.5
B	1156.0	1300.7

(2) There is the more direct relationship between the cyclic property and the fatigue behavior of material

The cyclic property is a macro-property which presents in strain fatigue and so it seems to be no relation to stress fatigue behvior. In fact, any process of fatigue is controlled by the plastic deformation in the local micro-zone. The cyclic property of material in the local micro-zone affects directly fatigue crack initiation and propagation.

It is shown from S-N curves of A and B specimens (see Fig. 3) that the fatigue behavior of B specimen is higher than that of specimen, although the monotonic $\sigma_{0.2}$ of A specimen is higher than that of B specimen. During stress fatigue, the strain is accumulated in the local micro-zone of specimen. For B specimen, the increase of cyclic yield strength is due to the cyclic hardening of material in the strain accumulation zone, while for A specimen, the decrease of cyclic yield strength is decided by the cyclic softening of material in the strain accumulation zone. Othermore, the change of the strain hardening exponent would occur in the process of fatigue. It can be seen from Tab. 2 that the $\sigma'_{0.2}$ of B specimen is higher than that of A specimen and the n' of B specimen is lower than that of A specimen. Therefore, B specimen exhibits higher slipping resistance in the micro-zone and higher fatigue behavior than that of A specimen. It is concluded

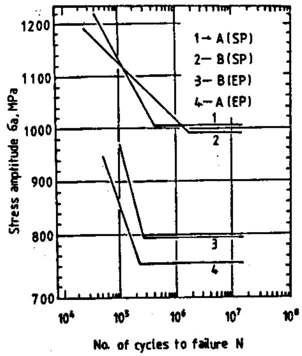
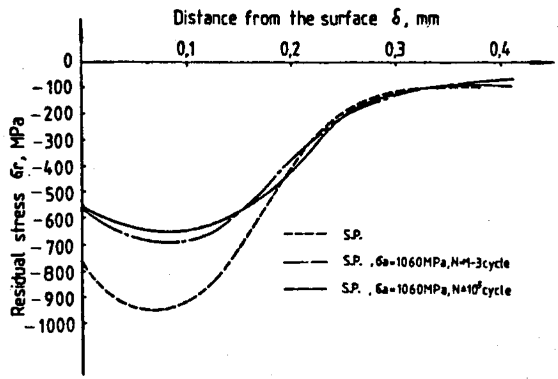


Fig. 3: S-N curves of both shot peened (SP) and electrolysic polished (EP) specimens



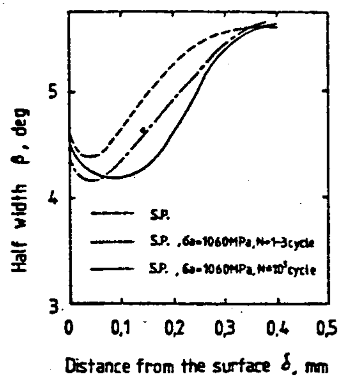


Fig. 4: Change of RSF during fatigue process

Fig. 5: Change of β-δ curve during fatigue process

from above mention that the fatigue behavior is closely related to the cyclic property ($\sigma'_{0.2}$ and n') of material. The higher the cyclic yield strength $\sigma'_{0.2}$ and the lower the cyclic strain hardening exponent n', the higher the fatigue strength.

SP is, in fact, a process of unsymmetrical push-pull strain. In fatigue test for peened specimen, the material in the surface layer undergoes stress fatigue after the cyclic strain during SP. It can be duduced that the cyclic hardening materials can act as microstructure strengthening and the cyclic softening materials as microstructure weakening. However, for the peened specimen the fatigue behavior under room temperature depeneds strongly upon RSF induced by SP and then the microstructural effect. The further study about the effect of the cyclic property on the fatigue behavior of peened material should be continued in the future.

2. SLR of RS and the optimum RSF

(1) SLR of RS is a damage relaxation

It is shown that the RSF induced by SP would relax during the fatigue process, as shown in Fig. 4. The rapid relaxation of RSF, that is, about eighty percent of the total value of the residual stress relaxation occurs at the initial fatigue stage (SLR stage). At the medium and last fatigue stage, the relaxation of RSF is slow and small, tending to a stable state gradually (DLR stage). It can be seen that the RSF induced by SP is a dynamic field during the fatigue process.

The SLR is a result of serious plastic deformation in the surface layer of material. It is shown that dislocation density decrease sharply at the early few cycles (see Fig. 5). This is caused by the annihilation of dislocations with opposite signs in their movement under the applied load. On the other hand, during deformation process the dislocations can pile up at the grain boundaries, phase boundaries and other obstacles. Once the stress reaches to the critical value due to dislocation pile up, the microcracks would occur. Obviously, the material in the surface layer would be damaged because of the existence of the microcracks and the fatigue crack will firstly propagate from these damaged points. When the main fatigue crack propagates to a certain length, other microcracks will be stopped due to the stress relaxation. These stopped propagation microcracks are called as "the damage microcracks". It is belived that the SLR at the initial fatigue stage is a damage relaxation.

(2) Optimum RSF

Based on above statement, if RSF induced by SP relaxes in advance to a stable RSF without damage before fatigue process, SLR will be avoided during fatigue process from which the optimum RSF can be obtained. In general, there exist two ways to relax RS, one of which is to apply load resulting in the stress relaxation and other of which is that the stress relaxation can be caused by the recovery of plasticaly deformed microstructure in heating. It is obvious that the RS relaxation caused by the latter, namely heat activation, could not indroduce any damage into the material under a certain condition. Therefore, the lower temperature temper after SP can be used to relax RSF before the fatigue test.

For GC - 4 steel, the regime of temper (300°C, for 5h) is chose considering that the ultimate tensile and yield strength could not change basicly after temper. The results has shown that the RSF after tempering is similar to that after SLR and keeps a good cyclic stability, as shown in Fig. 6 and Fig. 7.

Fig. 8 gives the S-N curves of both peened and peened plus tempered specimens. It can be seen that the fatigue limit of the peened plus tempered specimens is a little lower than that of the peened. However, in the higher alternating stress range of S-N curve, which is the range of the serious SLR, the fatigue life of the peened

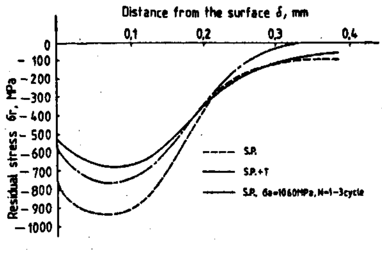


Fig. 6: RSF induced by SP after tempering

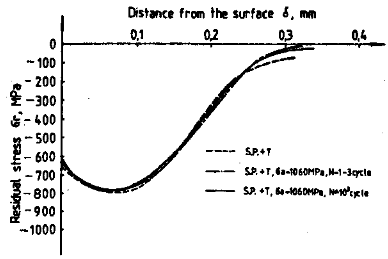


Fig. 7: Change of RSF induced by SP after tempering during fatigue process

plus tempered specimen is much longer than that of the peened. To prove further the effect of damage caused by the SLR on the fatigue behavior, two groups of specimen were prepared by the treating regimes listed in Tab. 4. It can be seen that the fatigue life of the second group with the optimum RSF is about ten times longer than that of the first group with the damage caused by the SLR.

Tab. 4 Average value of cycles to failure $\bar{N}_f$ (σ_a=1060 MPa)

No.	Specimen treatment	$\bar{N}_f$, cycle
1	SP + One to three cycles + Tempering (300°C, 5h)	1.728×10^5
2	SP + Tempering (300°C, 5h)	1.449×10^6

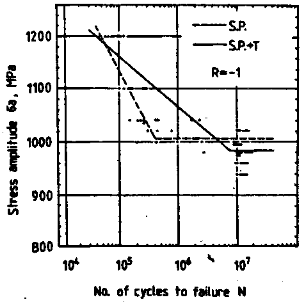
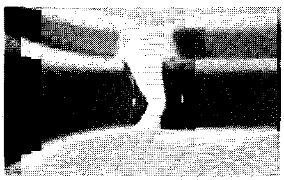
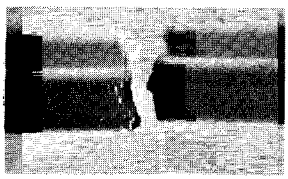


Fig. 8: S-N curves of both peened and peened plus tempered specimens

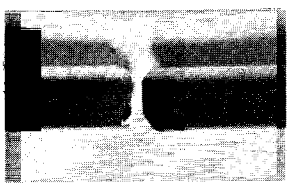
The result of the florescence examination of both specimens after fatigue is identical with the result of the fatigue tests, as shown in Fig. 9. At the same stress amplitude 1000 MPa, there is no damage microcracks on the surface near the facture surface for both specimens. This illustrates that the RS relaxation in the low alternating stress range is not enough to damage the material in the surface layer. When the stress amplitude increases to 1040 MPa or 1100 MPa, the damage microcracks are found only on the peened specimen. Obviously, it is a result of damage due to SLR. When the stress amplitude increase continuously to 1200 MPa, the damage microcracks occur on the surfaces near the facture surface for both specimens. The reason is that the damage caused by the SLR is not the main factor of crack initiation. It is seen that the optimum RSF can be obtained by means of tempering after SP for the mechanical components borne higher alternating stresses.



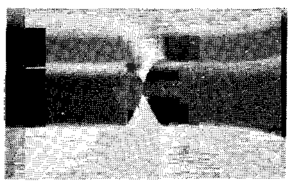
σ_a = 1200 MPa



σ_a = 1100 MPa



σ_a = 1040 MPa



σ_a = 1000 MPa

Fig. 9: Photographs of the florescence examination (The left is the peened, the right is the peened plus tempered in every photograph)

Conclusion

The results obtained may be summarized as follows:

1. Shot peening is a cyclic strain process.

2. There is more direct relationship between the cyclic property and the fatigue behavior of materials. The higher the cyclic yield strength and the lower the cyclic strain hardening exponent, the higher the fatigue strength of materials.

3. The static and dynamic load relaxation of residual stress field induced by shot peening would occur during the fatigue process. The static load relaxation is a damaged relaxation which is harmful to the fatigue properties of materials.

4. Shot peening plus tempering is an effective way to obtain the optimum residual stress field for the component borne higher alternating stress, resulting in a great increase of the fatigue life.

Reference

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