THE EFFECT OF SHOT PEENING ON ROLLING CONTACT FATIGUE BEHAVIOUR AND ITS CRACK INITIATION AND PROPAGATION IN CARBURIZED STEEL

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ABSTRACT

A series of rolling contact fatigue tests have been done by us using a carburized steel with and without shot peening. Continuous observations were carried out for the initiation and propagation of cracks. The distribution and change of the residual stress in the course of the rolling were measured. The changes of microtructure were observed with TEM. Distributions of retained austenite before and after shot peening were determined by x-ray. The contact fatigue lifetime is elongated and the crack propagation rate decreased by shot peening. In the course of the rolling, the high residual stress induced by shot peening has not relaxed after repeated rolling contact. On the basis of experimental investigations, the effect of shot peening on rolling contact fatigue behavior in carburized steel was analysed, which will be valuable for practice.

KEYWORDS

Shot peening; Rolling contact fatigue; Crack initiation and propagation ; Residual stress; Retained austenite; Carburizing.

INTRODUCTION

Carburization is widely employed in gear production. But some times on the surface of carburized parts the hardness is dropped by some defects (oxidization , decarbonization, non-martensite structures and so on) formed during carburizing, and the residual tensile stress will appear on the surface,so that the fatigue strength is decreased. It is well known that the bending fatigue life of the carburized gears can be increased remarkably after shot peening. [1-2] But the carburized parts like gears not only break by alternative bending stress, but also spall due to alternative contact stress. Up to now the researches about the effects of shot peening on rolling contact fatigue behavior are not enough.[3-5] Most of them were confined to the comparision of the lifetime and the analysis of the surface residual stress. In order to widely apply shot peening into gears and other carburized parts, our studies on the initiation and propagation of contact fatige cracks, the change of residual stress in the course of rolling are very important.

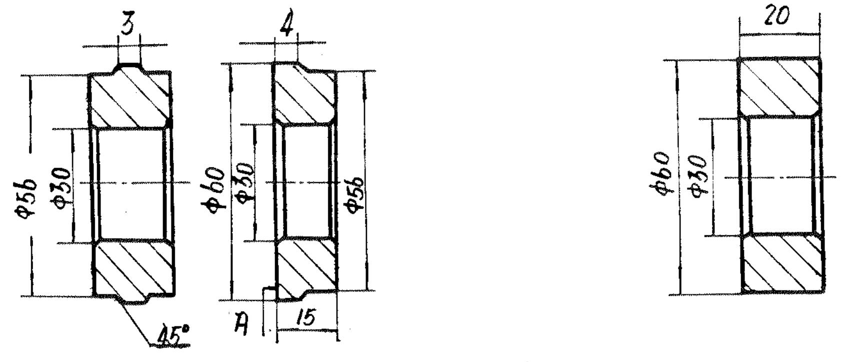
EXPERIMENTAL CONDITIONS

The steel 20CrMnTi was used, which is widely used for automobile gears in China. Its chemical composition are shown in Table 1.

Table 1: Chemical Composition of Material (wt.%)

Material	C	Si	Mn	P	S	Cr	Ti
20CrMnTi	0.21	0.26	1.00	0.02	0.017	1.10	0.08

Upper rollers with symmetrical shape were used in rolling contact fatigue life test,with nonsymmetrical shape were used in the test of observation of contact fatigue cracks. But their lower rollers are the same.Their shapes and sizes are shown in Fig. 1.



Symmetrical Non-symmetrical
(a) Upper roller (b) Lower roller

Fig.1. Shapes and sizes of rollers

The specimens were treated in a American carburizing furnace CJ-4467. The process is shown in Table 2.

Table 2: Carburizing heat treatment process

Area	1	2	3	4	5	Oil	Wash	Temper
T(C)	900	930	930	900	850	90	80	190
C.P.(%)	(N)	1.0	1.15	1.05	0.9	(Non-control)		
P.G.(M/h)	6	8	12	12	17			
Time(h)	The cycle is 0.5 hour.					0.1	0.1	3

C.P.--Carbon Potential   P.S.--Protective Gas

After heat treated, the surface hardness is about HRC 61.5; the core hardness is HRC41; the effective depth of hardened case (HV550) is about 0.95mm;the microstructures in surface layer are martensite and retained austenite about grade three, and the carbide is less than grade one (according to Chinese standard).

Half of the specimens were treated in a Japanese stress peening machine HC-34 after carburizing heat treatment. The process and the results are shown in Table 3. The surface hardness after shot peening is about HRC 63.

Table 3: Shot Peening Process and Results

Diameter	Hardness	Material	Flow	Time	Cover rate	ALMEN
0.8MM	HRC48-55	STEEL	100Kg/min	3*4min	>100%	0.56MM

In order to observe the initation of the microcracks on side-surface A (see Fig.1), the side-surface was ground 1 mm after the treatments to remove any strengthening layer and was polished at last.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Distribution of Microhardness

The distribution of microhardness in the hardened cases before and after shot peening were determined and are shown in Fig. 2. Fig. 2 shows that the depth of work hardening layer induced by shot peening is about 0.4 mm.Its hardness is obviously raised, by HV 50--80 or more. The obvious raise of the microhardness in the surface layer is a combined result caused by strain hardening, residual stress and the change of micro-structure.

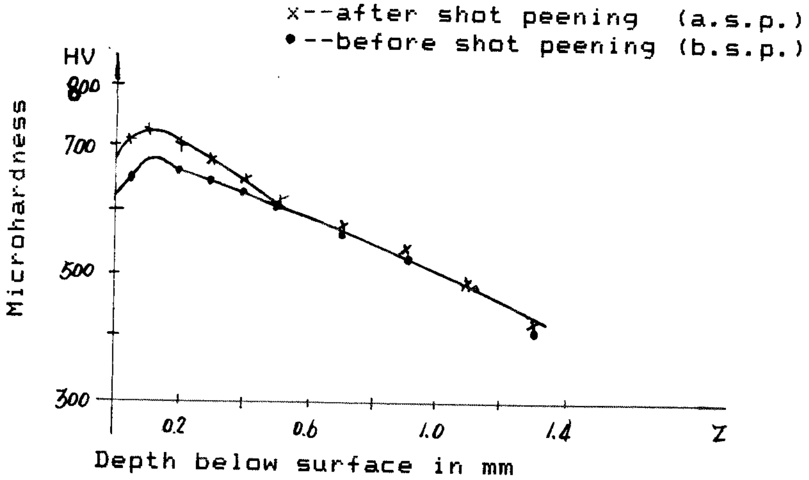


Fig. 2:
Distribution of microhardness

Distribution of Retained Austenite

The distributions of retained austenite on the surface layer of specimens were measured with a Japanese D/max--3AB X-ray diffraction instrument before and after shot peening.

Table 4: The Test Conditions of Retained Austenite Measurement

X-rey tube	Co	Filter	Fe
Tube current	20 mA	Scan speed	6°/min
Start angle		96°	107°
Stop angle		103°	114°
Diffraction crystal face		(211)α	(311)γ

The experimental conditions are shown in Table 4. The chemical corrosion method was used for denudation. The experimental results are shown in Fig. 3.

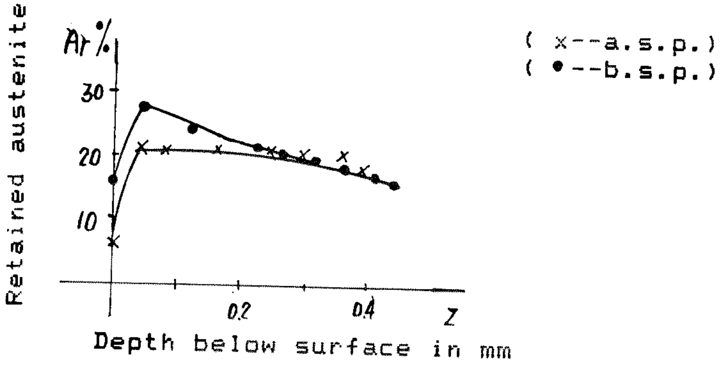


Fig. 3:

Distribution of retained austenite

From Fig. 3, we know that the reduction of retained austenite induced by shot peening is about 20% within the depth of 0.3mm, and reduced by 62.24% on the surface.This obvious reduction of the retained austenite is the result of the transformation of microstructure.

Distributions of Residual Stress

The distributions of residual tangetial stress in the surface layer of specimens were determined with a Japanese MSF--2M X-ray stress measurer before and after shot peening. The experimental conditions see Table 5.The experimental results are shown in Fig.4

Table 5: The Text Conditions of Residual Stress Measurement

X-ray tube	Cr	Filt	V
Tube voltage	30 kV	Tube current	6 mA
High angle	165°	Low angle	142°
Diffraction crystal face		(211)	
Stress coefficient		30.33	

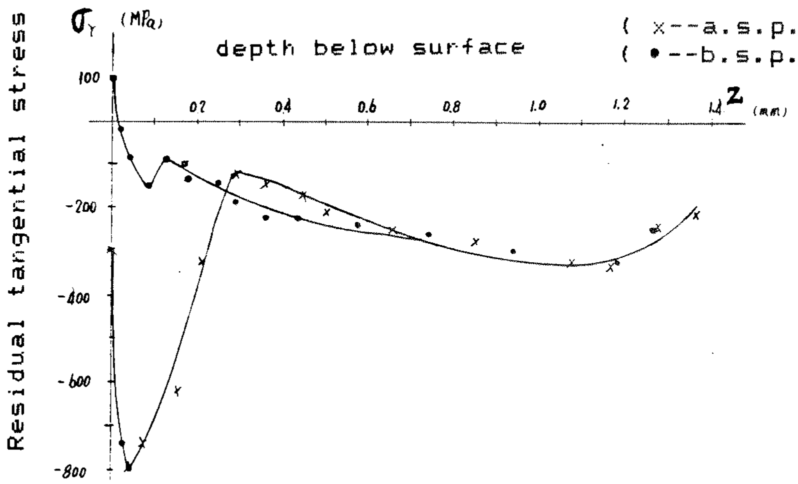


Fig. 4: Distribution of residual stress

Fig. 4 shows that there exists remarkbale compressive residual stress within the depth of 0.5mm induced by shot peening. Its maximum value is up to -800 MPa. However, before shot peening,the compressive residual stress is very small in this layer and there is tensile stress on the surface.

Electron Microscope Observation

In the layer 0.1 to 0.2mm beneath the surface the microstructures were observed before and after shot peening by using TEM. The obvious raise of the dislocation and the twin densities were discovered. Meanwhile, among some Martensite needles a lot of small needle-like constitute were found with Z or N shapes in this layer after shot peening, see Fig.5.

(a) 10000X (b) 10000X (c)40000X

Fig 5. Microstracture in the layer 0.1-0.2mm(TEM)
(a)Before shot peening,(b) and (c) after shot peening,with train-induced martensite

Based on the above measurements of microhardness and retained austenite, we found that the small needles in Fig. 5 are some train-induced martensite caused by shot peening.

Contact Fatigue Texts

A rolling contact testing machine JPM-1 (made in China) was used. Engine oil 20# was press fed into the roller pair. The oil temperature was below 50°C. In order to modelling the working condition of gears, the sliding ratio -5% was used. The curves of maximum contact Hertz stresses, σ max, vers the rolling cyclic number, lgN, are shown in Fig. 6.

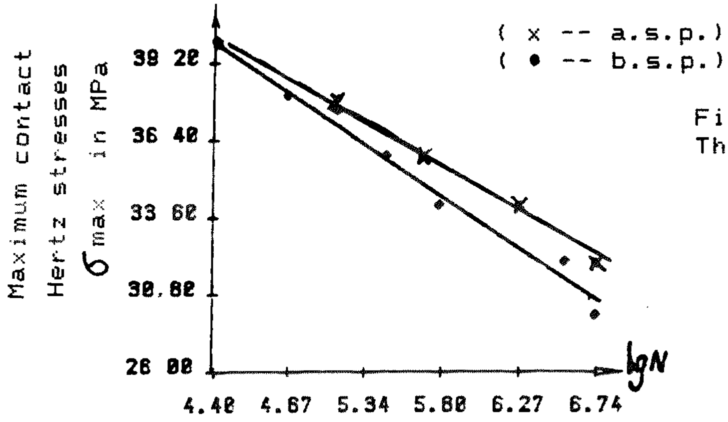


Fig. 6:
The σ max--LgN curves

Some equations of these curves can be made as follows by computer.

$$\text{Before shot peening:} \quad \sigma_{max} = 575.54 - 40.04 \lg N \quad (\alpha = 0.01)$$
$$\text{After shot peening:} \quad \sigma_{max} = 580.64 - 38.11 \lg N \quad (\alpha = 0.01)$$

From Fig.6 and two equations, we know that after shot peening the contact fatigue lifetime can be obviously elongated. Under the condition of N=5000000 cycles, the contact fatigue limit of the shot-peened specimens will be 5.9% more than those specimens without shot peening. But the slopes of the two linear are different, and under lower stresses the effect induced by shot peening seems more effective . Under the condition of σ_{max}=3050 MPa, the contact fatigue lifetime will be raised by 38.87% through shot peening.

Change of The Residual Stress During The Process of The Repeated Contact Rolling

After shot peening, the distribution of residual tangential stress during earlier stage of different rolling cycles were measured and are shown in Fig. 7.

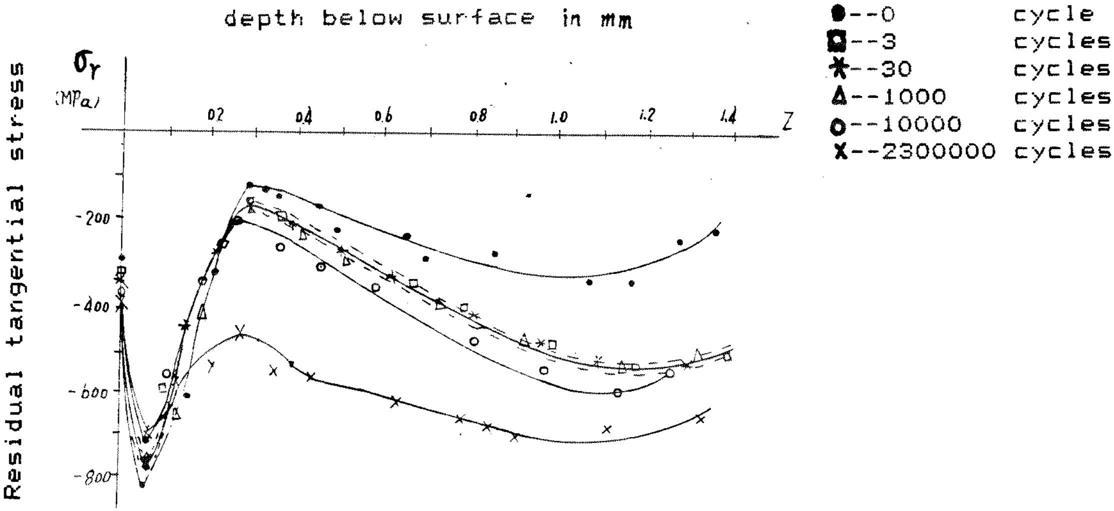


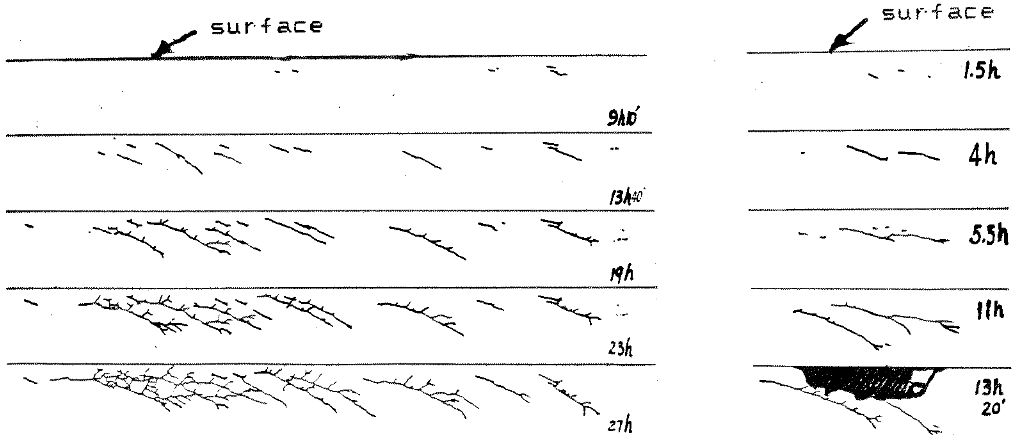
Fig.7: Distributions of residual stress after different rolling cycles (σ_{max}=3500MPa)

Fig.7 shows:(1)the residual stress induced by shot peening do not change approximately during the earlier stage of rolling and the compressive residual stress increases a little on the surface with the rolling cycles increased. (2)During the later stage, the compressive residual stress increases remarkably in the hardened layer of the specimens. (3)The depth of the peak residual stress induced by shot peening do not change with the rolling cycles. The peak values (about -800 MPa) decrease a little in the middle and late of the rolling life. These experimental results are quite different from other studies on the effect of shot peening in the bending fatigue tests [6-9].

It is quite evident that little change of the residual stress (induced by shot peening) in the long process of the rolling can produce a good effect on the fatigue behavior,restrain and retard the initiation and propagation of cracks, especially during later rolling cycles. This compresssive stress induced by shot peening can effectively offset or reduce shear stress, τmax45 and τxz, which cause the initiation and propagation of these cracks.

The Initiation and Propagation Process of Contact Fatigue Cracks

During the contact fatigue rolling test, the machine was stopped regularly and the specimens were observed under an optical microscope. Once the micro-cracks were observed on the side-surface of the specimens, the crack pattern was recorded photographically or traced using tracing paper on the screen of microscope. By continuous tracing the crack pattern at certain intervals of time the whole development process of contact fatigue cracks was recorded. The crack propagation drawings were obtained. A typical crack propagation drawing is shown in Fig. 8.



(a) With s. p. (b) Without s.p.

Fig. 8: Typical crack propagation drawing (σmax=3230MPa)

The so-called intersection point method [10] was adopted for statistics and analysis on the development process of cracks. Fig. 9 is a schematic diagram showing this intersection point method. The propagation drawing was covered by a piece of tracing paper with the square network on it.The horizontal lines parallel with the specimen rim-surface. It is obvious that the variation in the total number of intersection points reflects the total propagation rate of the crack growing toward the rim-surface of the specimen.The typical relation curves between the total number of intersection points of each crack, M, and the corresponding rolling cycles ,N, are shown in Fig. 10.

After statistic treated , some parameters describing the development process of cracks can be obtained. The results are given in Table 6.

Table 6: Parameters Describing the Development of Cracks

State	Nucleation life (No)	Initiation depth (mm)	Fatigue life (Nf)
Without s. p.	342000	1.20	1550000
With s. p.	700000	1.02	7760000

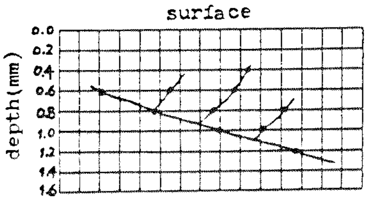


Fig. 9: Schematic diagram of the intersection point method

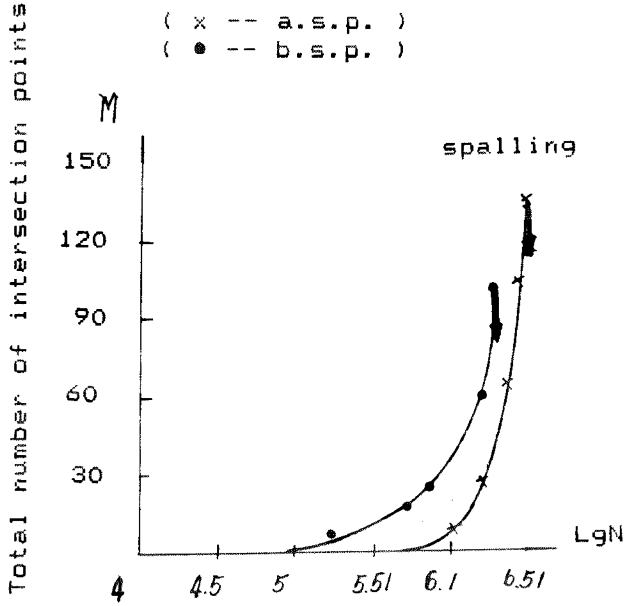


Fig. 10: M-LgN curves (σmax = 3230 MPa)

Fig. 10 and Table 6 show that the initation depth becomes shallower and the nucleation and propagation lives of the contact fatigue cracks can be elongated by shot peening , the rate of cracks propagtion decreases obviously during the later stage. These results indicate that after shot peening the specimens not only have those behaviors already studied [11], but also with some further features: (1).The angle, θ ,between the main cracks and the friction direction of the surface is deceasing when cracks grow toward the rim-surface, and tends to 0° as soon as the cracks grow into the effective layer of shot peening; but becomes larger when the cracks grow toward the core of specimen, and tends to 90° at last. (2).when the cracks propagate toward the rim-surface, the rate of propagation decreases, and some new branching cracks initiatc once again from the old cracks in the effective layer of shot peening. (3). Although there exist some shallow cracks on the rim-surface after shot peening, they do not propagate further.

CONCLUSIONS

(1).The contact fatigue limit(when N=5000000 cycles)can be raised by 6%, or the contact fatigue life can be elongated about 30% at the lower contact stress by shot peening in the carburized steel 20CrMnTi.The lower the stress, the longer the life will be.

(2). After having been carburized and shot peened, the cracks nucleation lifetime increases, the cracks propagation rate decreases, especially during the later stage, and the mode of cracks propagation in the surface layer is different from those specimens without shot peening. The shallow cracks on the surface formed by shot peening are nonpropagating cracks.

(3). The high residual compressive stress induced by shot peening would be not relaxed during the rolling process.

(4). After having been carburized and shot peened, the cpecimens micro-hardess is raised, the defects are decreased, part of the retained austenite is transformed into the train-induced martensite,the dislocation density is increased,the substructures are refined in the surface layer.

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