The Research to the Contact Fatigue Behavior Influenced by the Residual Stresses on the Surface of the Shot-peened Specimens

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Abstract

This paper describes the influence of surface work-hardening layer and high residual press stresses produced on the rolling specimens of 20CrMnTi steel after Heat-treatment and shot-peening on contact fatigue behavior. On the condition of our experiments, the main forms of contact fatigue failure are deep-spalling and shallow-spalling. Surface work-hardening layer and residual press stresses can repress the formation of surface cracks and retard the propagating speed of cracks, so that its contact fatigue lifetime can be greatly increased. This paper presents a diagrammatic modol for the distribution of residual surface stresses and the behavior of their function.

Introduction

The main types of failures for gears in cars and tractors are bending fatigue, contact-fatigue and wear,etc. Among these types, contact-fatigue and wear take heavy percentage, so that the study of gears on contact-fatigue, wear and the rules of their influence is the key problem for the increase of the property and lifetime of gears.

There are three types of contact fatigue failure in gears, that is, pitting-spalling, shallow-spalling and deep-spalling. Pitting-spalling generally nucleates on surface of a specimen. Shallow-spalling is caused either by cracks on surface or by ones nucleated in subsurface. Deep press spalling is caused by cracks nucleated in the transition zone between hardening layer and matrix. For comparison, the lifetime of deep-spalling and pitting-spalling is the shortest, that of shallow-spalling caused by crack nucleated on surface is next, and that of shallow-spalling caused by cracks nucleated in sub-surface is the longest [1,3]. These rules show directions we must follow, that is, first, we should harden surfaces of specimens so that cracks are not liable to produce on it, second, we should increase the thickness of hardening layer or harden the matrix to reduce deep press spalling.

For many years, carburizing technique has been the main Heat-treatment technique for gear surface hardening. If a certain technique is applied to harden the surface further and bring in high residual press stresses on surfaces of specimens, it is possible to improve its properties. According to this view-point, we have applied shot-peening technics to the gear production after carburizing, which increases the properties of gears greatly.

Experimental conditions

1, Specimens and material.

We use rolling specimens in our experiment. Both main and matching specimens have the same diameter of 50mm and the surface finish of $\nabla 7$. The length of contact line is about 4mm. The chemical compositions of 20CrMnTi steel of which our specimens are made are shown in Table.1.

2, Course of Heat-treatment of specimens.

After pre-heat-treatment and machining, the specimens were heat-tre-

Material	C	Cr	Mn	Ti	P	S
20CrMnTi	0.21	1.08	1.0	0.03	0.02	0.009

Table.1: Chemical compositions of specimens(%).

ated finally; First, carburized at the temperature of 930 C for 7 to 8 hours, then taken out and directly quenched in oil after being pre-cooled, finally tempered at the temperature of 180 C for 2 hours . The surface hardness of specimens after being heat-treated is about HRC 60 to 61.5; the center hardness HRC 39 to 40.5; the depth of carburizing layer about 1.2mm; the micro-structures of surface layer are martensite and retained austenite(about the 5th degree); and the carbonide is the second degree.

3. Shot-peening process.

The diameter of steel shots is about 0.8 to 1.0mm; peening velocity: 60m/s; surface finish before and after shot-peening: 0.68um(CLA) and 0.7um(CLA); peening time: 4.5min and ALMEN intensity: F = 0.6mm.

4. Equipment of the experiment.

The contact fatigue experiment was done on the JP - BD 1500 contact fatigue test machine using lubricant oil of 20# with some additives for lubrication and cooling. The tempetature of oil was controled at less than 50°C to guarantee the existance of oil film during operation. When greater than 2x2mm spalling pits or visible cracks appear on the surface of specimen, the machine stops automatically and the number of cycle is taken down.

Results and discussion

1. The feature of micro-structure on the surface layer.

By microscopic observation, we find that the micro-structures on surface layer of specimens which were carburized, quenched and shot-peened are finer than that which were only carburized and quenched. The working hardened layer induced by shot-peening is 0.25 to 0.3mm, under which, including carburizing layer, transition zone and matrix structure, all specimens have the same structure, whether they were shot-peened or not.Because of intensive shot-peening at high speed, the micro-structure of surface layer and sub-grain are refined and dislocation density increased, which result in hardening effect. The surface layer of specimens of shot-peening after carburizing quenching becomes shot-peening work-hardening layer. its hardness is obviously raised,about HV 100 to 150 and over, as shown in Fig.1.

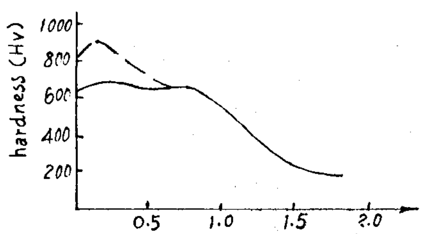


Fig.1: Hardness distribution before and after shot-peening.

2. Residual stresses on surface layer of specimens.
The residual stresses on the surface layer of specimens were measured with XLY -74 x-ray stress measurer, as shown in Table.2.

Direction of stress	specimen after C.Q		after C.Q + S.P	
	main (N/mm)	matching (N/mm)	main (N/mm)	matching (N/mm)
Tangential stress	-390	-500	-610	-880
Radius stress	-440	-560	-705	-930

C.Q + S.P means Carburizing-quenching and Shot-peening.

Table. 2: Residual stresses on surfaces of specimens.

3. Results of contact fatigue experiment.
In order to imitate the real working condition of gears, slade difference of 19.7% was used in the contact fatigue experiment. The maximum contact Hertz stress can be calculated with Hertz formulae:

$$max = 0.418\sqrt{\frac{P.E}{L}\cdot\frac{R1+R2}{R1.R2}}$$

In the formulae:
E - elastic modulus(about 210000 N/mm^2),
P -applied load,
R1,R2 - radius of main, matching specimens respectively,
L - contact length of the two specimens.

The σmax - lgN contact fatigue curves measured are shown in Fig.2 in which it can be found that shot-peening can obviously increase

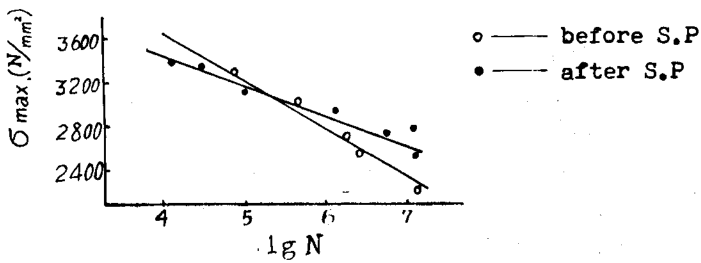


Fig.2. The σmax - lgN contact fatigue curves.

the contact fatigue lifetime at high cycle. For instance, under the condition of σmax = 2300 N/mm^2, the contact fatigue lifetime of the specimen which is shot-peened is 4.7 times as high as that of the specimen which is not shot-peened. The contact fatigue limit of the specimen being shot-peened is 2560 N/mm^2 and the non-shot-peened 2180 N/mm^2. The linear equations can be made as follows:

Specimens before shot-peening:

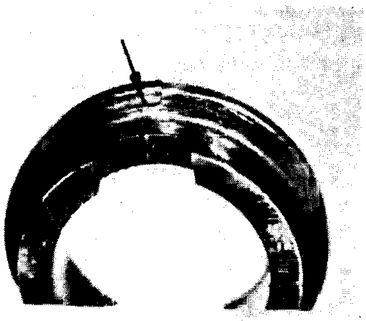
$$\lg N = 10.428 - 0.00157\,\sigma max$$

Specimens after shot-peening:

$$\lg N = 13.631 - 0.00259\,\sigma_{max}$$

4. Fractography of contact fatigue failure.

Experiment shows that under the condition of slide difference of 19.7%, the main types of contact fatigue failure are shallow spalling and deep-spalling, as shown in Fig.3.



(a). deep spalling.

(b). shallow spalling.

Fig.3: The fractography of contact fatigue failure.

The course of spalling may be divided into three stages, i.e., crack nucleation, crack propagation and final fracture, in much the same way as other courses of fatigue failure.Under the action of higher contact stresses, deep- spalling with the depth of 1.0 to 1.2mm, corresponding to hardened layer and transition zone of matrix, appears on the specimens both before and after shot-peening. Fatigue crack nucleates in the transition zone, then propagates parallel to the surface, and finally failures as it becomes longer.Under the action of lower stresses, shallow-spalling generally appears after more cycles. Crack mostly nucleates on the surface of specimen without shot-peened(see Fig.4.) while that mostly nucleates in the sub -surface of specimen after shot-peened(see Fig.5.). Obviously, it

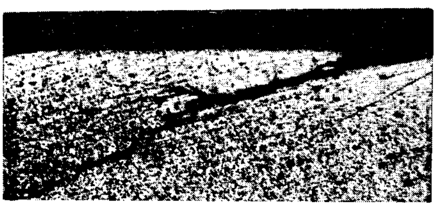


Fig.4: Crack nucleating on surface of specimen before shot-peening.

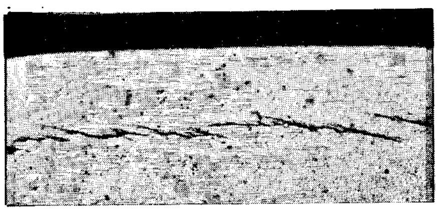


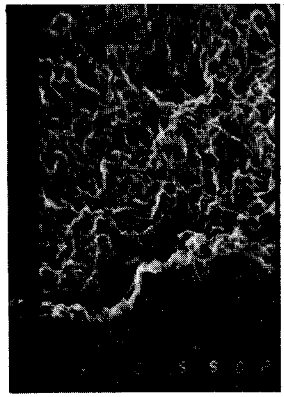
Fig.5. Crack nucleating in subsurface after shot-peening.

is difficult for crack to nucleate and propagate in sub-surface.In other words, the contact fatigue lifetime is long.

For the shallow-spalling with which crack nucleates on surface, the lubricating oil as it enters into crack, induces additional stresses which increase the propagating speed of crack and make spalling occur quickly.

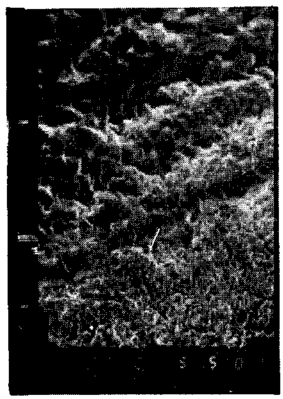
For the shallow-spalling with which crack nucleates in sub-surface, first, the crack propagates slowly in vacuum after being formed in sub-surface, then it propagates quickly when it emerges to surface due to the oil entering in, and the action of added oil wedge, and finally spalls, so that the lifetime is long.

(a) crack origin



(b) crack emerging zone

(c) rapidly propagating zone



(d) final fracture zone

Fig.6. SEM photos of fracture of a specimen after shot-peening.

Corresponding SEM photos are as above: Fig.6.(a) : crack origin, the marks of friction and pressure around it which is slowly propagating zone under vacuum, (b): crack emerging zone, (c): rapidly propagating zone, with obvious propagating steps,(d): final fracture zone.

5. Discussion.

Rolling specimens were used in our experiment, and according to the relation of Hertz stress, the distribution of contact stresses under contact area is shown in Fig.7.

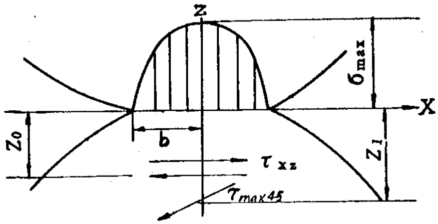


Fig.7: Distribution of stresses under rolling contact area.

From Fig.7, we know that under the action of contact stresses, the maximum shear stress $\tau max45$ which is in 45° angle with contact area and τxz which is parallel to contact area are formed in the subsurface. The value of shearing stress $\tau 45$ pulsates in 0 to $\tau max45$. τxz is alternate symmetry stress. The distribution of the two stresses is shown in Fig.8(a). In the Fig:

b - half width of contact area.

$$b = 1.52\sqrt{\frac{P}{E.L}\cdot\frac{R1.R2}{R1+R2}}.$$

$$\tau max45 = 0.3\sigma max.$$

$$\tau xz = 0.25\sigma max.$$

$$Z_0 = 0.5b,\ Z1 = 0.786b.$$

We consider that τxz plays an important part in the formation of crack. Under the condition of existance of slide difference, the maximum of τxz will move from 0.5b to the surface, as shown in Fig.8 (b), because of additional action of friction.

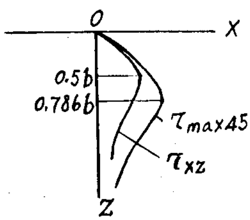


Fig.8(a): Distribution of τ max and τ xz.

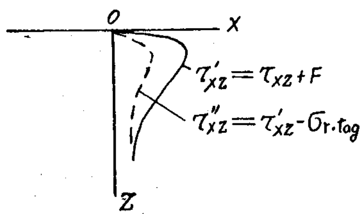


Fig.8(b): The maximum value of τ xz will move to the surface due to the action of friction(F).

After being carburizing quenched and shot-peened, the surface work-hardened layer of specimen raises the strength of surface layer. Meanwhile, due to the action of shot-peening, high tangential and radius press residual stresses are induced on the surface layer, which, especially tangential press residual stress, can effectively offset or reduce τ_{xz} which is parallel to the contact surface, as shown by the dotted line in Fig.8(b).

Theory analysis and results of experiments show that the work-hardening resulted from shot-peening and the occuring of residual press stresses restrain the nucleation of surface cracks and compress them to form in sub-surface, which result in shallow-spalling, so that the contact fatigue lifetime in the condition of high cycles and low stresses can be raised. The course of crack nucleation resulted from sub-surface is shown approximately in Fig.9. The repeating action of τ_{xz} caused by the repeating action of contact stress enables dislocations near the highest value of τ_{xz} under contact surface to slide unequally , stop up, form small holes gradually. These holes which are pressed flat can be connected together to form micro-cracks. The nucleation period of micro- cracks is very long and they propagate slowly in vacuum. We propose the diagrammatic sketch on

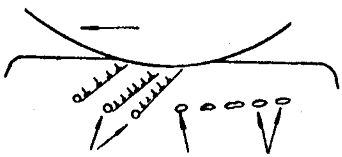
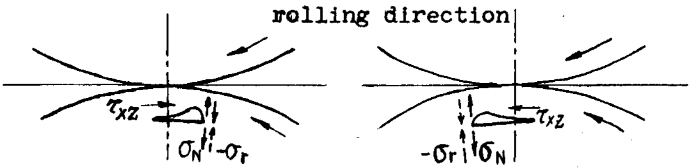


Fig.9: Diagrammatic sketch of crack nucleation in sub-surface.



(a): The left hand side of the crack enters into central line.

(b): The left hand side of the crack leaves the central line.

Fig.10: Diagrammatic sketch on crack propagation and stress analysis in sub-surface.

crack propagation and stress analysis, as shown in Fig.10. During the course of sliding and rolling contact fatigue rotation, the upper surface of the crack(in one side of specimen surface)under the repeating action of τ_{max45} and τ_{xz} will be elongated plastically along the direction of τ_{xz}, which causes the two upper tips of crack, especially left upper tip to bend, so that the stress σ_N is formed, which makes the tips of crack propagate parallel to the specimen surface. After being shot-peened, residual pressed stress in radius direction is induced on the surface of specimen, which can reduce or partly offset σ_N, retard propagating speed da/dN of crack. Only when crack appears on the surface, can lubricating oil enter, additive oil wedge be formed, which makes crack propagate rapidly and failure.

Conclusions

1, The surface layer structure and sub-grain of 20CrMnTi steel after being carburizing quenched, tempered and shot-peened can be fined. Network carbide can be eliminated and dislocation density increased. 0.15 to 0.3mm work-hardened layer can be formed and hardness value can be 100 to 150 HV higher than that after being carburizing hardened and tempered.
2, While surface is hardened by means of carburizing quenching plus tempering and shot-peening, high residual pressed surface stress is induced. The value may be -880 to -930 N/mm^2 or higher, which greatly increase contact fatigue lifetime($\sigma\ max \leqslant 3000\ N/mm^2$). The deep-spalling can be produced because of lower hardness in the center or transition zone when $\sigma\ max > 3000\ N/mm^2$.
3, The three main forms of contact fatigue failure on specimens after being carburizing quenched, tempered and carburizing quenched, tempered plus shot-peened are deep-spalling, shallow-spalling nucleating on surface and shallow-spalling nucleating in sub-surface. The contact fatigue lifetime of specimen nucleating in sub-surface is the longest, that of specimen nucleating on surface is the next and the deep-spalling the shortest. The contact fatigue lifetime of specimen after being carburizing quenched, tempered plus shot-peened is the longest because the shallow-spalling nucleates in sub-surface . The course of contact fatigue failure is as follows: nucleating-slowly growth in vacuum - fast propagating when crack appears on surface - failure.
4, The technique of shot-peening is simple and it is a useful technique for surface hardening of gears and other parts to increase their contact fatigue lifetime.

References

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