EFFECT OF SHOT PEENING ON THE PITTING FATIGUE STRENGTH OF CARBURIZED GEARS

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ABSTRACT

There are many reports to indicate that shot peening is a valid means to improve the bending strength of gear teeth, but there are only a limited number of reports on its effect on pitting fatigue strength and its mechanism is yet to be understood clearly.

The authors investigated the conditions under which pitting of truck and bus transmission gears occurs and conducted a roller pitting fatigue test and a gear pitting fatigue test using spur gears in order to evaluate the effects of shot peening on the pitting fatigue strength of carburized gears.

The findings obtained from the tests are listed below:

(1) Pitting of carburized gears originates from the intergranular oxidation area on the surface produced by carburizing.
(2) Shot-peened gears excel in both fatigue limit and fatigue life.
(3) Electron microscopy of the sliding surfaces indicated that the residual compressive stress, which develops as a result of shot peening, works to suppress opening (cracking) of the intergranular oxidation layer under the Hertz's contact pressure and consequently improves the pitting fatigue strength.

KEYWORDS

shot peening, carburized gear, residual stress, pitting fatigue,

The transmission gears for trucks and buses are now required to have higher strength in order to cope with increasingly higher engine outputs and to meet requirements for longer life.

Usually, the transmission gears for trucks and buses are made of Cr-Mo steel, Cr steel or some other carburized steel and are left as carburized after cutting (shaving) for cost and productivity considerations.

In the case of specific gear combinations used mostly due to special conditions in foreign countries, however, the bending fatigue fracture of gear teeth, pitting and spalling (hereinafter referred to collectively as pitting) fatique or other problems sometimes occur with such gears.

There are many reports (1) - (6) to indicate that shot peening is a valid means to improve the bending fatigue strength of gear teeth and this is achieved by selecting an optimum peening condition to give a high residual compressive stress to the tooth face.

There are only a limited number of reports (7) on the effect of shot peening on the pitting fatigue strength of carburized gears and its mechanism (8),(9) is yet to be understood clearly.

The authors investigated the conditions under which pitting of truck and bus transmission gears occurs and conducted a roller pitting fatigue test and a gear pitting fatigue test using spur gears in order to evaluate the effects of shot peening on the pitting fatigue strength of carburized gears. The report of the tests and their results follows.

TEST METHOD

Investigation of Field Durability Test Gears

Figure 1 shows a cross section of a typical truck and bus transmission components.
Generally, the 2nd and 3rd gears shown in Figure 1 suffer bending fatigue fracture of the gear teeth most often, while the overdrive gear and constant-speed gear suffer pitting fatigue most often.

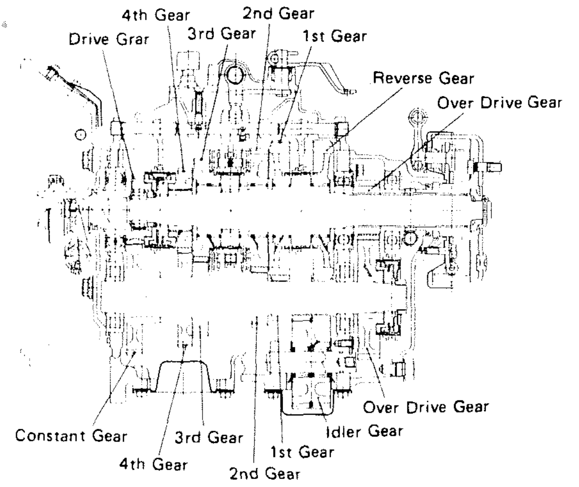


Fig.1 Cross Section Showing Transmission Components

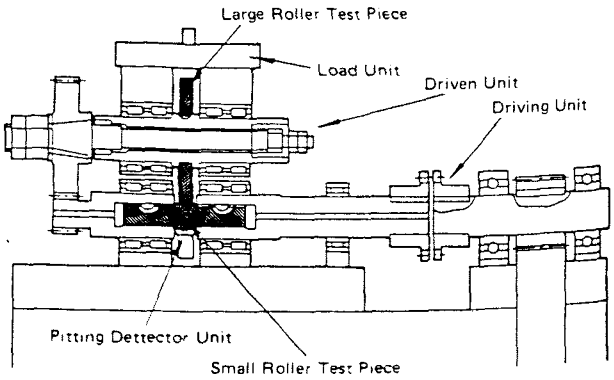


Fig.2 Roller Pitting Fatigue Test Apparatus

The sliding surfaces and cross sections of the carburized gears that developed pitting during the field durability test were observed through an electron microscope.

Roller Pitting Fatigue Test

Test Apparatus. The test machine used in this test is a roller pitting fatigue tester that operates using sliding contact of a roller-shaped test piece under a high contact pressure. Figure 2 shows the apparatus.
The small roller test piece was held constant at 1000 r/min and the specific sliding was set at 40%, which is equivalent to the maximum specific sliding of an ordinary transmission gear.
For the detection of pitting, an automatic pitting detector, employing an optical fiber to measure the change in the reflectivity of the test piece sliding surface, and a vibrometer mounted to a loading lever to measure the change in the vibration were used.

Test Pieces. Figure 3 shows the shape of the test pieces used. They were made of Cr-Mo carburized steel, the chemical composition is listed in Table 1 and the heat treatment conditions are shown in Figure 4.

Tab.1 Chemical Composition

Material	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
Cr-Mo Steel	0.24	0.24	0.89	0.015	0.008	0.11	1.13	0.21	0.12

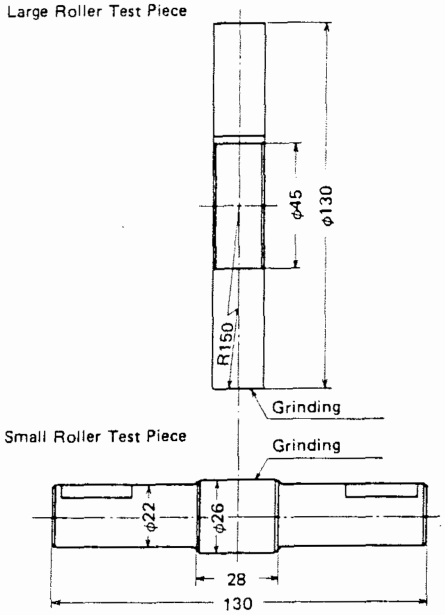


Fig.3 Test Piece Design for Roller Pitting Fatigue Test

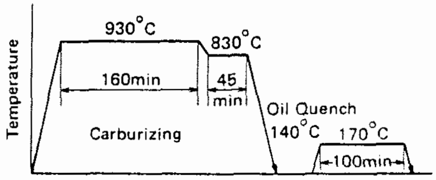


Fig.4 Heat Treatment Conditions

Half of the identically-prepared test pieces were shot peened under conditions that are feasible in commercial production. The shot peening conditions are listed in Table 2.

Table 3 lists the properties of both the carburized test pieces and the shot peened test pieces after carburization (hereinafter referred to as the shot-peened test pieces).
Residual stress distribution of the sliding surfaces of the test pieces, before and after testing, were compared using the X-ray diffraction method.
As for the pitting fatigue test pieces, pitting on their surfaces and cross sections was also observed through an electron microscope.

with a kinematic viscosity of 87.0 x $10^{-6}m^2/s$ at 40°C and 10.5 x $10^{-6}m^2/s$ at 100°C.

The lubricant was applied between the test pieces under pressure at a rate of 0.5 liter/min, the oil temperature being 80±3°C.

Tab.2 Shot Peening Specifications

	Specification
Arc Height(Almen Strip A)	0.7mmA
Coverage	300% Min.
Shot Size	ϕ0.6 ~0.8
Hardness of Peening Media	HRC53 ~55
Projection Verosity	68m/sec(Estimation)

Tab.3 Properties of Small Test Pieces for Roller Pitting Fatigue Test

	Carburized Test Piece	Shot Peened Test Piece
Surface Hardness	HV 730	HV 840
Effective Case Depth (HV550)	0.7mm	0.7mm
Core Hardness	HRC 35	HRC 35
Depth of Intergranular Oxidation	22 μm	22 μm
Surface Residual Stress	+160 MPa	-480 MPa
Max. Residual Compresive Stress	-180 MPa	-1340 MPa

Gear Pitting Fatigue Test

Test Apparatus. The apparatus used for the tests was a gear pitting fatigue tester using power circulation (10) as outlined in Figure 5, with the large gear running at a constant speed of 1500 r/min (the small gear at 1890 r/min). After a run-in period, the tester was operated continuously with a constant load. During the run-in period, the load was increased in steps from the 1st stage to one stage before the test stage according to the load stages in Table 4 (the Hertz's contact pressure shown in this paper does not take dynamic load into account). Each load stage was held for 15 minutes. Then, at the test load stage, operation was maintained until serious surface damage was caused by pitting.

As for the gear life assesment, after a given period of operation the test gear was removed from the tester and its weight lost through wear was measured. Gear life was determined to be the total revolutions of the small gear before the amount of wear due to pitting started to increase sharply.

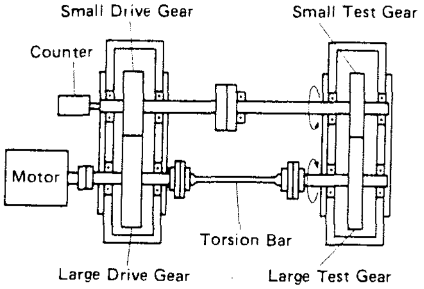


Fig.5 Gear Pitting Fatigue Test Apparatus

Tab.4 Load Stages

Load Stage	Torque of Pinion M_1 N m	Hertz's Contact Pressure at Pitch Point P_H ,MPa b=5mm
1	10	495
2	50	1107
3	100	1566
4	150	1918
5	200	2215
6	250	2476
7	300	2712
8	350	2930
9	400	3132
10	450	3322

Test Gears. The gears tested were spur gears of module m=3 (small gears with number of teeth Z_1 = 27, large gears with number of teeth Z_2 = 34). Table 5 lists their dimensions.

In order to increase the contact pressure without loss of gear tooth strength, the large gears had a face width of b = 20mm and the small gears had on effective contact width of b = 5 mm with 0.3 mm level difference in the tooth trace direction. The tooth shape of the small gears is shown in Figure 6.

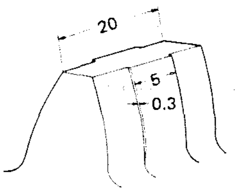


Fig.6 Tooth Profile of Small Test Gear

Tab.5 Dimensions of Test Gears

	Large Gear	Small Gear
Type of Gear	Spur Gear	
Tooth Profile	Full Depth Tooth	
Module	3	
Cutter Pressure Angle	20°	
Number of Teeth	34	27
Amount of Addendum Modification	0	
Diameter of Generating Pitch Circle mm	102	81
Diameter of Tip Circle mm	108	87
Crowning	0	
Accuracy	JIS 4 Grade	
Surface Finishing Process	Shaving	
Center Distance mm	91.5	

The test gears were of the same chemical composition and had the same heat treatment conditions as the test pieces in the roller pitting fatigure test.

Half of the identically-prepared gears were shot peened under the same conditions (Table 2) as the test pieces used in the roller pitting fatigue test.
Table 6 lists the properties of both the carburized test gears and the shot-peened test gears.

As with the roller pitting fatigue test pieces, the residual stress distribution of the test gears before and after testing were compared using the X-ray diffraction method. As for the pitting test gears, pitting on their surfaces and cross sections was also observed through an electron microscope.

Tab.6 Properties of Small Gears for Gear Pitting Fatigue Test

	Carburized Gear	Shot Peened Gear
Surface Hardness	HV 752	HV 835
Effective Case Depth (HV550)	0.7mm	0.7mm
Core Hardness	HRC 35	HRC 35
Depth of Intergranular Oxidation	15μm	15μm
Surface Residual Stress	-270MPa	-330MPa
Max. Residual Compresive Stress	-490 MPa	-990MPa

Lubricant. The lubricant used in the tests was equivalent to GL3 gear oil with a kinematic viscosity of 198 x $10^{-6}m^2/s$ at 40°C and 18.1 x $10^{-6}m^2/s$ at 100°C.
The lubricant was sprayed under pressure at the meshing point at a rate of 2.4 liters/min with an oil temperature of 60±3°C.

TEST RESULTS AND DISCUSSION

Field Durability Gears

The carburizing process currently applied in commercial production uses a carburizing gas with trace amounts of H_2O and CO_2, which causes oxidation of the steel surface during carburization.

When oxygen enters the steel, its diffusion rate is generally higher in the grain boundary than in the transgranular structure. Therefore, as oxygen enters the steel from the surface, Cr, Mn and Si move toward the grain boundary faster than other elements present in the matrix in the vicinity of the grain boundary. Then, the elements combine with the oxygen that has diffused and reached the boundary. This phenomenon is called intergranular oxidation.
Once this phenomenon occurs, the reduction in the amount of Cr amd Mn causes a loss of hardenability. As a result, in the vicinity of the area where intergranular oxidation is caused, martensitic transformation does not occur, but bainite and troostite are produced.

This phenomenon is unavoidable as long as ordinary gas carburizing is used, which always causes a thick intergranular oxidation layer of about 5 to 30 μm to be produced on the surface (the longer the carburizing time, the thicker this layer becomes).

The presence of an intergranular oxidation and structural anormalies were confirmed by electron microscopy of the tooth sections of a new, carburized gear as shown in Photo 1.

seen, pitting occurs typically from around the pitch circle of the teeth to the tooth roots.

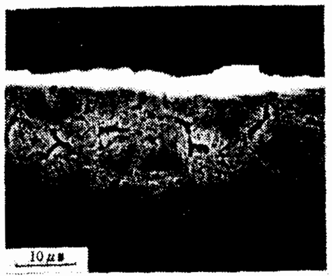


Photo. 1
SEM Micrograph of Surface Structural Anomalies

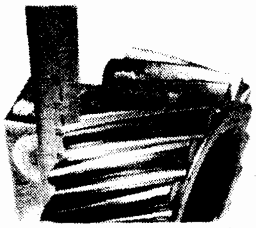
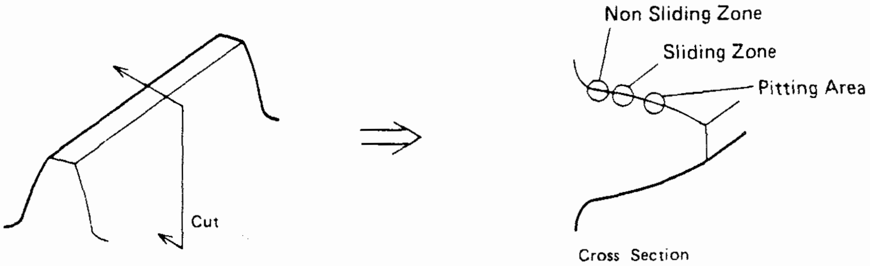
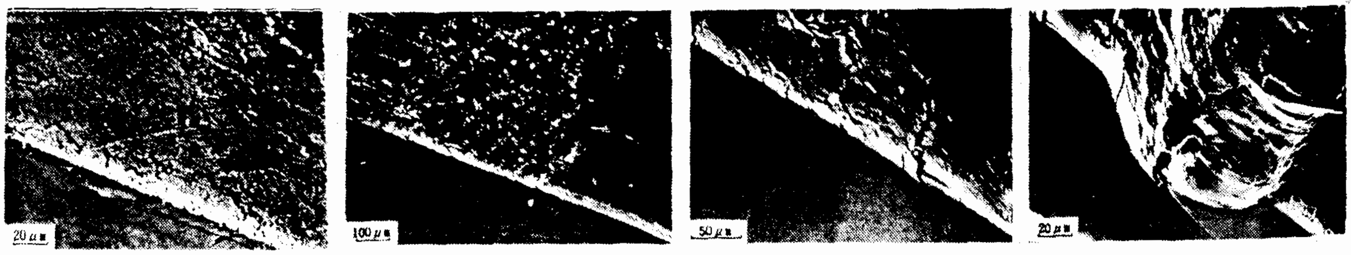


Photo. 2
Pitted State after Durability Test

The result of observation by electron microscope of these pitted areas on the surface and cross section is shown in Photo 3. It can be seen that plastic flow developed under the surface from around the pitch circle to the tooth roots and that the pitting originated from intergranular oxidation, as discussed earlier.

Some theorize that pitting originates from immediately below the surface where maximum Hertz's stress occurs, but from the results presented above, it is believed that in the case of carburized gears, the intergranular oxidation on the surface is the origin of crack, which then propagates to cause pitting.





Non Sliding Zone Sliding Zone Sliding Zone (Magnification) Pitting Area

Photo.3 Observation by SEM of Tooth Surface after Durability Test

Roller Pitting Fatigue Test

Fatigue Diagram. The results of the roller pitting fatigue tests of the carburized pieces and the shot-peened pieces, conducted under the above test conditions, are plotted with the tooth strength P_H on the ordinate and the life N to generation of pitting on the abscissa (semi-logarithmic scale) (Figure 7). It can be seen from the diagram that the shot-peened pieces have about 1.15-times higher fatigue limit at 2 x 10^7 cycles and about 10-times longer life under 3200 MPa Hertz's contact pressure.

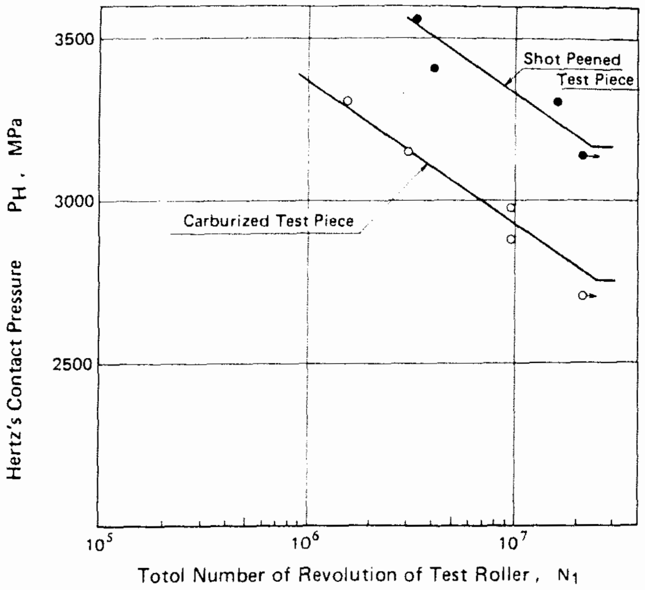


Fig.7 Results of Roller Pitting Fatigue Test

Residual Stress. Figure 8 shows the residual stress distribution as determined by using the X-ray diffraction method on the carburized pieces and the shot-peened pieces, before and after testing.

The comparison of the carburized pieces and the shot-peened pieces before testing indicates that the former had a tensile residual stress of about 200 MPa on the surface and that the shot-peened pieces had about 500 MPa compessive residual stress on the surface. It can also be seen that under that shot peening conditions employed, the maximum residual compressive stress of about 1300 MPa occurs at a depth of 50 μm below the surface.

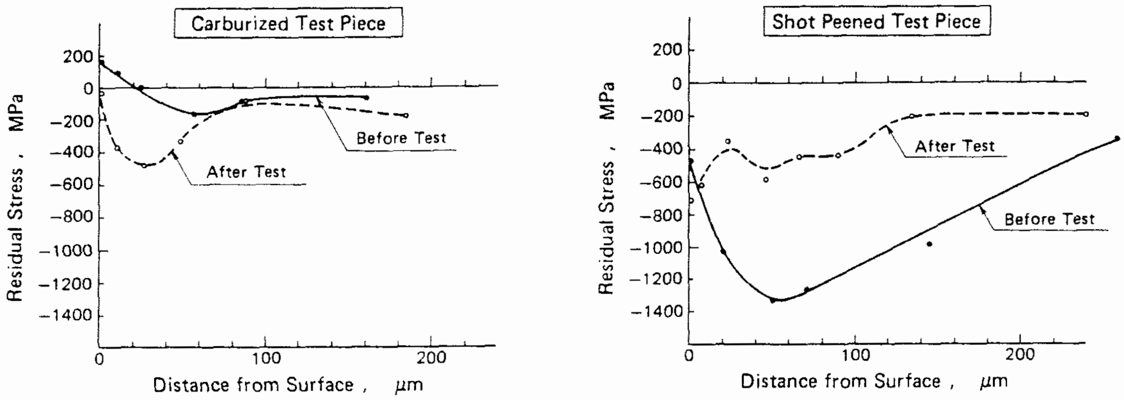


Fig.8 Residual Stress Distribution of Roller Pitting Fatigue Test Piece

The degree of improvement in the residual compressive stress and that of the pitting fatigue strength do not necessarily correspond, but it is believed that this improvement in the residual compressive stress contributes to that of the pitting fatigue strength.

The measurement of the residual stress on the sliding surface after testing indicated a decrease in the internal residual compressive stress of the shot-peened pieces. In the vicinity of the sliding surface, however, a residual compressive stress probably due to the pressure of the mating roller was observed. In the case of the shot-peened pieces, the residual compressive stress on the surface was not changed significantly by the test.

Observation of Pitting. Photo 4 shows the typical pitting produced in the tests.

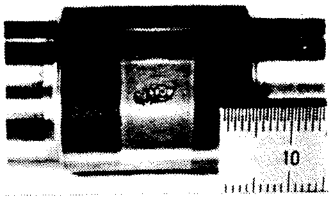
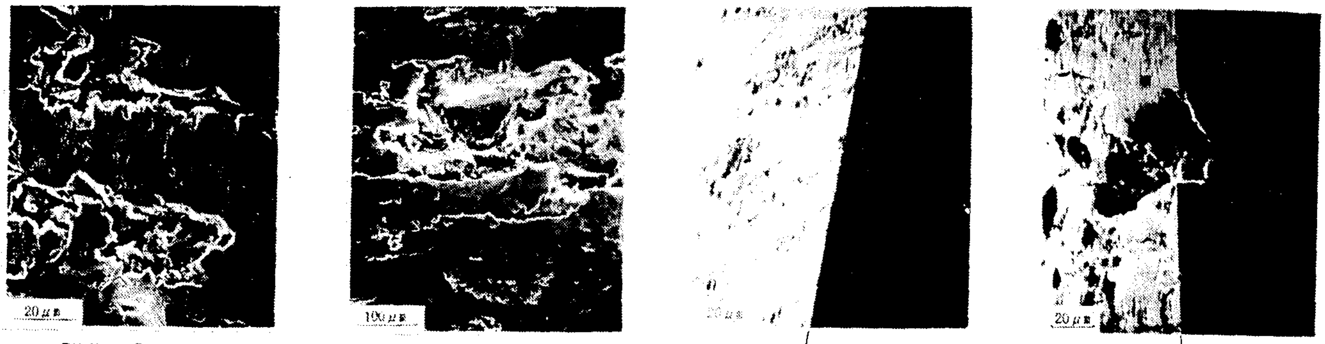


Photo. 4 Pitted State after Roller Pitting Fatigue Test

Photo 5 shows the surface and cross section of the pitted portions of the carburized test pieces and Photo 6 shows that of the shot-peened test pieces as observed by electron microscope.



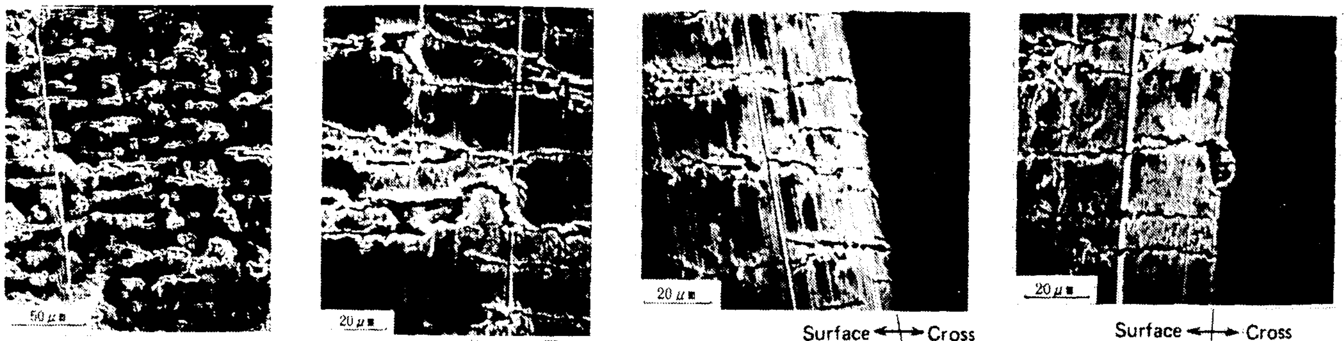
Sliding Surface

Pitting Area

Surface ← → Cross Section

Surface ← → Cross Section

Photo.5 Observation by SEM of Carburized Test Piece Surface after Test



Sliding Surface

Sliding Surface

Surface ← → Cross Section

Surface ← → Cross Section

Photo. 6 Observation by SEM of Shot-Peened Test Piece Surface after Test

From these photos, plastic flow is observed on the topmost sliding surfaces of the carburized pieces as in the case of the field test gears. It can also be seen that the pitting originated from the intergranular oxidation. On the sliding surfaces, many open cracks were observed.

On the low surface pressure portions of the contact surface side sections, many such shallow cracks were also observed, but separation originating from them was not observed. On the contact surface center (increasing contact pressure) side, the cracks were smaller in number and pitting occurred in the center of the contact surface where the contact surface pressure was the highest.

From these observations, it is believed that cracking originating from the intergranular oxidation starts in the early stages of cycling, stops for some time due to the internal residual compressive stress and then propagates to final destruction in subsequent cycling.

The shot-peened pieces also exhibit similar plastic flow and the pitting develops from the intergranular oxidation area with only the topmost surface plastically deformed by shot peening.
The cracks observed on the sliding surface, however, are closed in contrast to the open cracks seen in the carburized pieces. This is probably because the residual compressive stress stops the growth or propagation of cracking.
As can be seen from the fatigue diagram, the shot-peened pieces have a longer fatigue life probably because of this effect of the surface residual compressive stress that suppresses cracking and delays crack growth.

Gear Pitting Fatigue Test

Fatigue Diagram. Figure 9 shows the relationship between the tooth face strength P_H (Hertz's contact pressure at pitch point) of the carburized gears and the shot-peened gears tested under the above conditions and the life N_1 to pitting (total revolutions of the small gear). The straight lines shown in the figure are the linear regression curves obtained by the least squaring of the plotted data, except the large separated plot.
It can be seen that the shot-peened gears have about 1.35-times higher fatigue limit at $2x10^7$ cycles and about 28-times longer life under 3200 MPa Hertz's contact pressure.
The shot-peened gear data tends to have a larger scatter than that of the carburized gears.
The problem, therefore, will be how to achieve more uniform shot peening.

Residual Stress. Figure 10 shows the residual stress distribution of the sliding surface of the shot-peened gears before and after testing as determined by using the X-ray diffraction method.

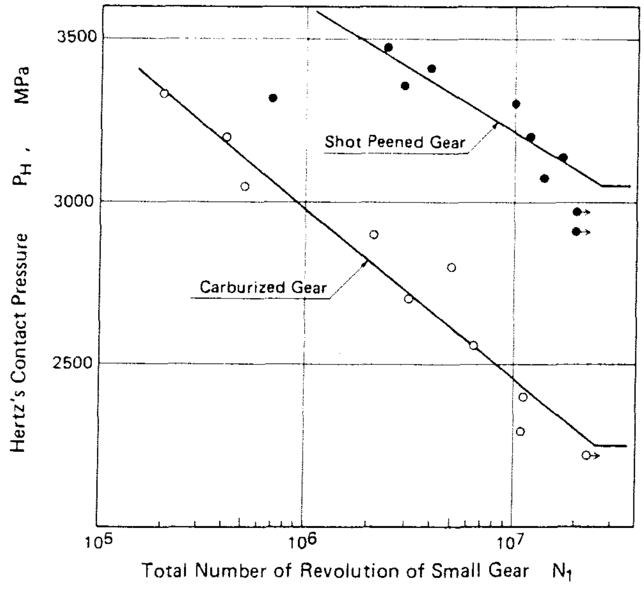


Fig.9 Results of Gear Pitting Fatigue Test

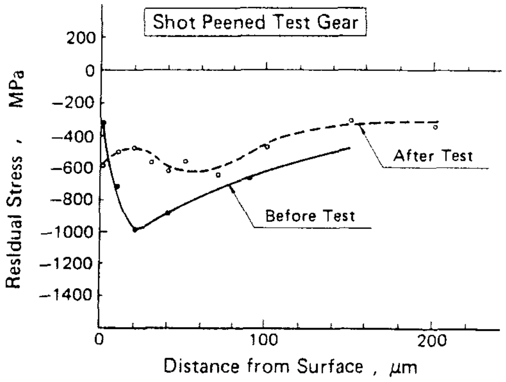


Fig.10 Residual Stress Distribution of Pitting Fatigue Test Gear

As in the roller pitting fatigue test pieces, a residual compressive stress was produced on the surface using shot peening, with a residual compressive stress of about 1000 MPa occurring at a depth of about 20 μm beneath the surface. The test gears were subjected to shot peening under the same conditions as the roller pitting fatigue test pieces and we thought that the difference in the resultant residual stress level was due to the differences in the test piece shapes.

A residual stress distribution pattern after the test similar to one obtained after the roller pitting fatigue test was obtained.

Observation of Pitting. Photos 7 and 8 show the typical pitting produced in the tests, along with enlarged views.
Photo 9 shows the surface and cross section of pitted portions as observed by electron microscope.
From these photos, it is believed that cracking originated from the intergranular oxidation layer and separation occurred therefrom, leading to pitting as in the roller pitting fatigue tests.
The cracks observed on the sliding surface are closed by the residual compressive stress of shot peening.

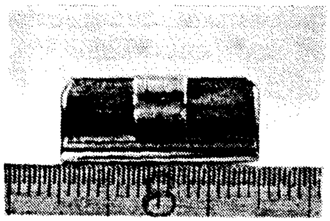


Photo. 7 Pitted State after Gear Pitting Fatigue Test

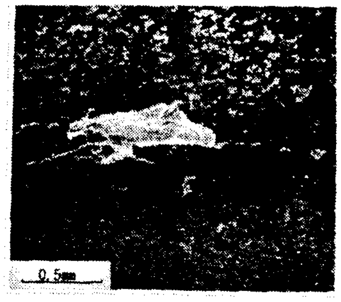


Photo. 8 Magnification of Pitting Area after Gear Pitting Fatigue Test

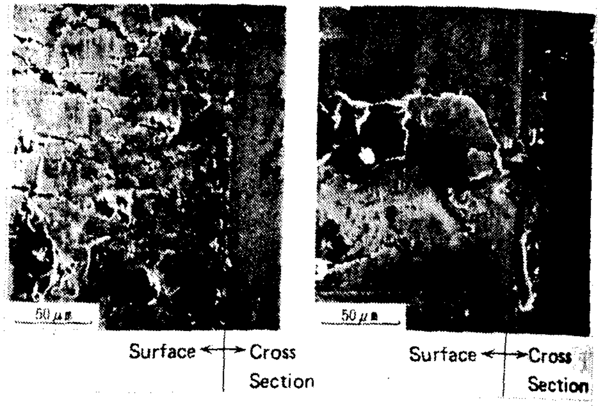


Photo. 9 Observation by SEM of Shot–Peened Test Gear Surface after Test

CONCLUSION

The test results and observations may be summarized as follows:

(1) Pitting of the carburized gears originated from the intergranular oxidation area on the surface produced by carburizing.

(2) The results of the roller pitting fatigue tests indicate that the shot-peened test pieces had about 1.15-times higher fatigue limit at 2×10^7 cycles and about 10-times longer life under 3200 MPa Hertz's contact pressure than the carburized test pieces.

(3) The results of the gear pitting fatigue tests indicate that the shot-peened gears had about 1.35-times higher fatigue limit at 2×10^7 cycles and about 28-times longer life under 3200 MPa Hertz's contact pressure than the carburized gears.

(4) The electron microscopy of the sliding surfaces indicated that the residual compressive stress developing as a result of shot peening works to suppress opening (cracking) of the intergranular oxidation layer under the Hertz's contact pressure and consequently improves the pitting fatigue strength.

ACKNOWLEDGEMENT

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