EFFECTS OF SHOT PEENING AND HEAT TREATMENT ON ENDURANCE LIMITS OF AUSTEMPERED DUCTILE CAST IRON GEARS

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ABSTRACT

ADI materials are going to be applied to transmission gears. Endurance tests of the ADI gears were carried out to discuss summarily the effects of shot peening and heat treatment on the endurance limits of bending strength as well as surface durability. It is clarified that the shot peened ADI gears are suitable to gear materials due to the increase of the endurance limits, although those gears have rough surface. At the same time, special precautions are required in utilizing the ADI with a low hardness of base material and in using of oil with no EP additives as the endurance limits are restricted by surface durability.

KEY WORDS ; ADI, Shot peening, Heat treatment, Gear endurance limit, Surface roughness, Bending strength, Surface durability, Lubricant, EP additive

INTRODUCTION

Recently, an austempered ductile cast iron (ADI) is going to be applied to the gear material because of having almost the same mechanical strengths as a steel(1)~(4). Furthermore, the material has well-known to have work hardening ability and less noise performance due to damping capacity of vibration. If it is applied actually to a gear material, it might result in the excellent performance of power transmission gears.

Endurance limits of power transmission gears have been conventionally designed both by bending strength and surface durability. Shot peened ADI gears must be anticipated to have the higher bending strength due to the compressive residual stress which would induce to the surface layer of tooth filet. They, however, have the rougher surface roughness than that of the gears finished by grinding. It might consequently deteriorate the surface durability of the power transmission gears.

In this paper, effects of shot peening, austemper heat treatments and lubricants on the endurance limits of ADI gears were comprehensively studied by using a power circulating type gear endurance testing machine in taking account for bending strength as well as surface durability. Advanced discussions are presented to apply ADI materials to transmission gears.

ADI MATERIALS USED IN THE TEST GEARS

Two different patterns of austenite and austemper heat treatment of an ADI material were used in the present experiments. The chemical compositions of the ADI material are shown in Table 1, and two patterns of heat treatment process are shown in Fig.1. One of the heat treatments, termed austemper treatment I in this paper, is austenited at 1173 K (900°C) for one hour and austempered at 573 K (300°C) for 3 hours, and the other one, termed austemper treatment II, is austenited at 1203

Table 1 Chemical compositions of ADI material

C	Si	Mn	Cu	Ni	Mo	Cr	Ti	Mg
3.40	2.64	0.39	0.19	0.01	<0.01	0.02	0.044	0.048

Table 2 Mechanical properties of ADI obtained by different austemper treatment

Austemper heat treatment	Proof strength (0.2% σ_s) (MPa)	Ultimate strength (σ_B) (MPa)	Elongation (%)	Reduction of area (%)	Absorbed energy (J)	Hardness (HB)
I	1162	1413	2.2	3.2	73	365
II	759	990	6.3	7.4	136	284

K(930°C) for 2 hours and austempered at 648 K (375°C) for 2 hours.

Fig. 2 shows the micro structures of the ADI obtained by each austemper treatment. The mechanical properties after austemper treatments are shown in Table 2. Their graphite sizes are approximately the same of about 30μm in both heat treatments. However, a base structure treated by austemper treatment I is sharper and finer acicular structure and less quantity of retained austenite than that of austemper treatment II. The mean retained austenite in the base structure of the ADI by austemper treatment I is about 10 %, but in the case of austemper treatment II is about 36%.

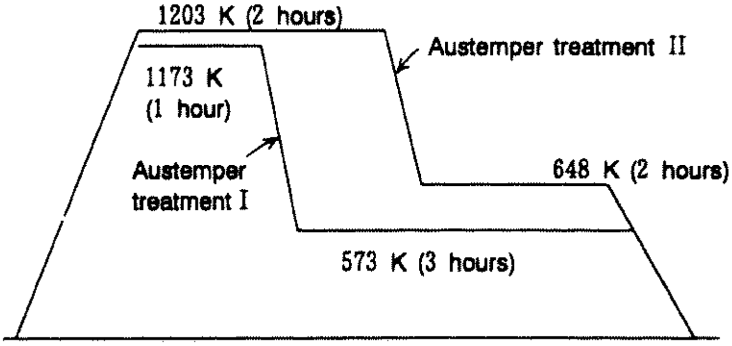
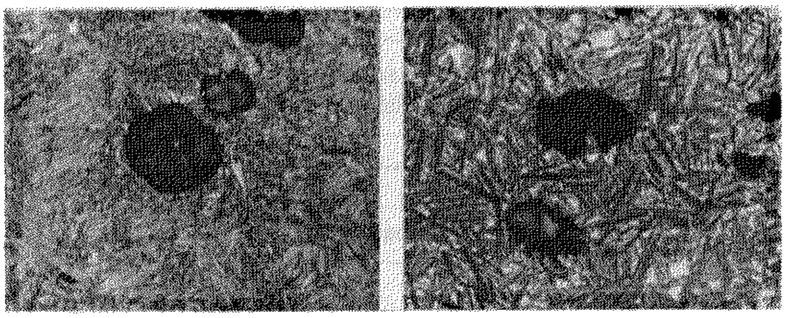


Figure 1 Heat treatment processes



(a) Austemper treatment I (b) Austemper treatment II

Figure 2 Micro structures of ADI material

TEST GEARS

A spur gear of which specifications are shown in Table 3 is used as the test gars. Manufacturing processes of the test gears are mainly classified into four groups. The processes after austenite and austemper heat treatments are shown in Fig.3. The first one, termed "NGA" process in this paper, was finished by grinding the tooth surface and tooth filet on a gear grinder after austemper treatments, but its tooth root corresponding to bottom land of tooth was as-hobbed. The second one, termed "NGB" process, was finished by grinding the tooth root as well as tooth surface and tooth filet after austemper treatments. The third one, termed "SPN" process, was additionally shot peened the whole surfaces. The tooth filet and tooth surface of the gears had been ground by a gear grinder before shot peening in order to minimize the influence of gear accuracies on endurance limits. Only tooth root, however, had been in the as-hobbed state. The fourth one, termed "SPG" process, was also additionally shot peened only tooth filet and tooth root of the gears but, before shot peening, the tooth surfaces were masked by cushion tape to maintain the accuracy and the smoother surface roughness. Therefore, the tooth surface of "SPG" group gears was maintained in as-ground surface state with no shot peening.

Grinding process was carried out by a gear grinder with a screw type aluminum oxide grinding wheel. Moreover, the shot peening was performed by the conditions shown in Table 4.

To simplify the terminologies, the test gears finished by "NGA" manufacturing process and heat-treated

Table 3 Specifications of test gears

Module	3
Pressure angle	20°
Face-width	10mm
No. of teeth	26
Helix angle	0°
Pitch dia.	78.00mm
Outer dia.	84mm
Contact ratio	1.62

Table 4 Shot peening conditions

Method	Pressure	Dia. of nozzle	Distance to work	Particle size	Hardness of particle	Arc height A scale	Duration
Air	200 kPa	9 mm	120 mm	0.3 mm	200 Hv	0.1 mm	60 s

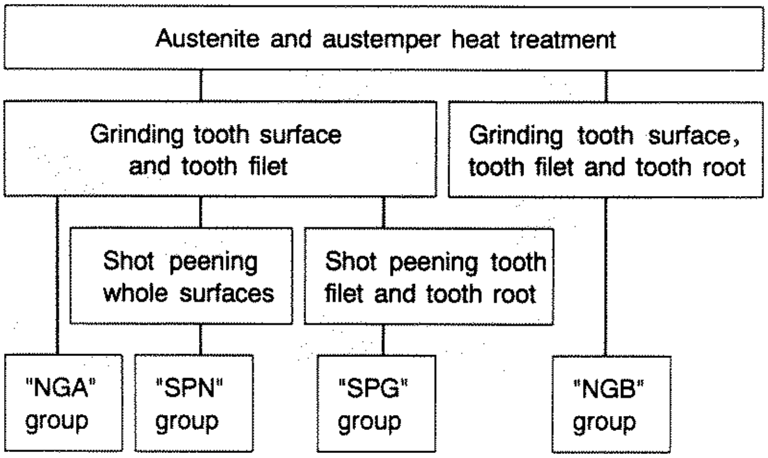


Figure 3 Manufacturing processes of test gears after heat treatment

by the austemper treatment I are called herewith "NGA-I". Accordingly, those gears, finally finished by shot peening after heat treatment II and subsequent grinding, are called "SPN-II".

Additional shot peening to the precise gears finished by the grinding might have been thought to deteriorate the accuracies of test gears. The accuracies of tooth profile and tooth trace of test gears are shown in Fig.4, and tooth space of them are shown in Fig.5. It is seen that the accuracies of "SPN" group gears are highly precise corresponding to ISO 5 grade or AGMA 11 grade even though the shot peening have been performed.

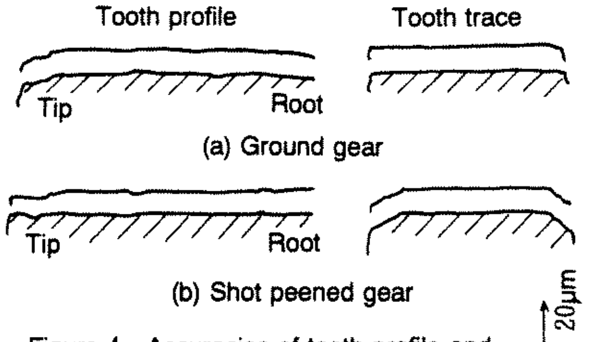


Figure 4 Accuracies of tooth profile and tooth trace of test gears

Surface roughness generally seems to affect the endurance limits of gears for surface durability and bending strength. Surface roughnesses of tooth surface of test gears finished by each processes are shown in Fig.6. They were measured by Talysurf roughness meter in direction of tooth profile at center of the tooth trace. The surface roughnesses of gears obtained by shot peening, termed "SPN" group gears, have a roughness of about 5μm Rmax (= 1.3μm Ra). In contrast to this, the surface roughnesses of gears finished by grinding have a roughness of about 3μm Rmax (= 0.7μm Ra). The surface roughnesses of tooth filet obtained by a grinding and a shot peening and that of as-hobbed tooth root are also shown in Fig.7. It is understood that each of ground and shot peened is almost the same as that of tooth surface, respectively. But that of as-hobbed has a roughness of about 10μm and then it is the roughest.

The residual stresses were measured by an X-ray diffraction method for advanced discussions. Fig.8 shows changes in residual stresses induced by shot peening to the surface layer of tooth root, tooth filet and tooth surface of gears in terms of "SPN" group in contrast with those of gears, termed "NGA",

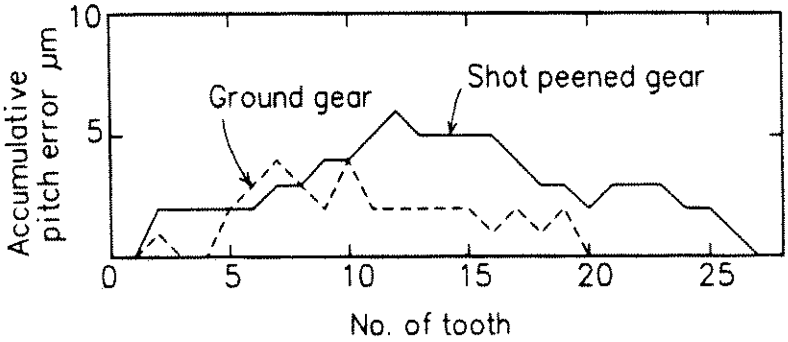


Figure 5 Tooth space errors of test gears

with no shot peening (shown in Fig. 9). In the case of "SPN" group gears, it is seen that deeper compressive residual stress was induced by additional shot peening to the whole tooth surface layer than that of "NGA" group gears finished by normal manufacturing process. In contrast to this, the surfaces of tooth filet and tooth surface of "NGA" group gears were finished by a gear grinding after austemper treatment so that shallow but large compressive residual stress induced by grinding to them but that of as-hobbed tooth root is a little tension.

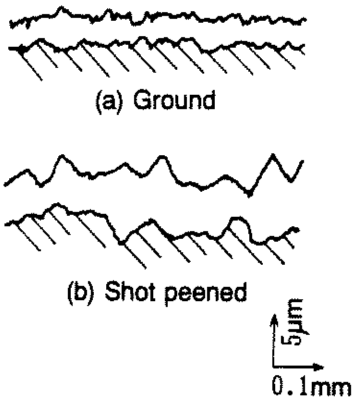


Figure 6 Surface roughnesses of tooth surface before running

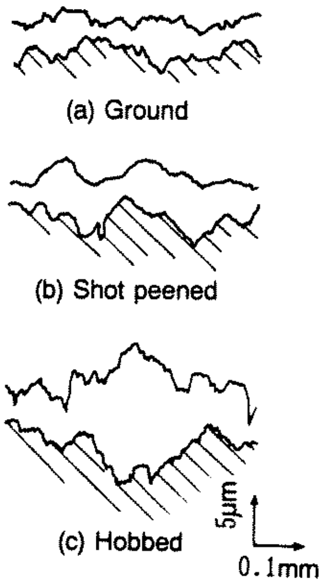


Figure 7 Surface roughnesses of tooth root before running

GEAR ENDURANCE TESTS AND TESTING MACHINE

Gear endurance tests were carried out on the power circulating type gear testing machine having a maximum circulating power of 40kW which has been made by the authors. In the endurance tests, the gear pairs with a whole-number gear ratio of a unity were used and rotated by

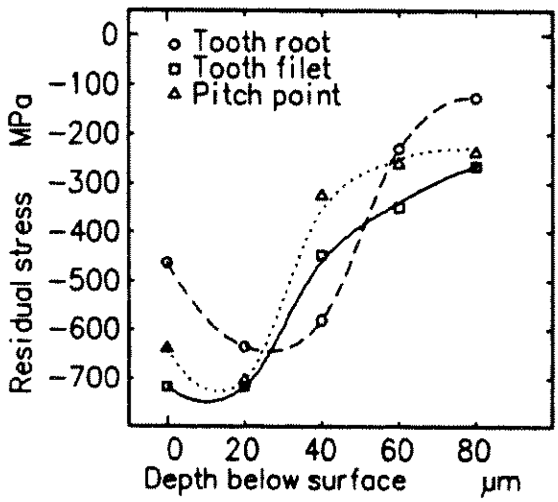


Figure 8 Residual stress distributions of shot peened gears before running

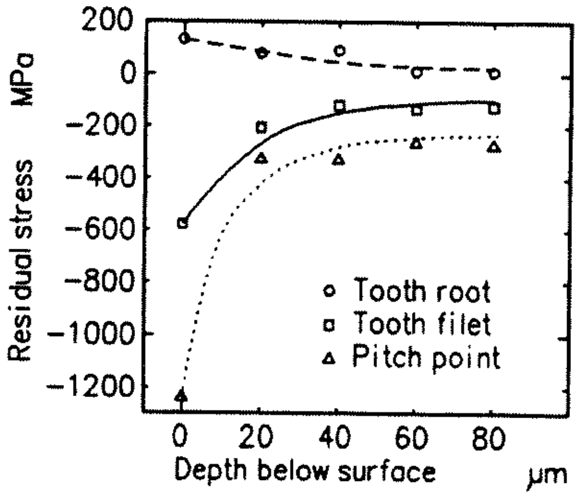


Figure 9 Residual stress distributions of ground gears with no shot peening before running

induction motor at a rotational speed of 1800 rpm.

A driving and a driven test gear, which had a tapered hole in boss, were mounted tightly and precisely to the corresponding shaft. Then load was applied statically by twisting the torsional shaft between test gears and power circulating gears. Otherwise, a pair of helical gears which had a wider face-width of 40mm than that of test gears of 10mm was used in the power circulating gears in order to reduce correlative fluctuation.

The endurance test was also carried out under the oil bath lubricating system for the consideration of the market use. Two kinds of lubricants, namely oil A and oil B, as shown in Table 5 were used in the present experiments. The first, mainly used in the experiments, was of the high viscosity and contained the extreme pressure (EP) additives of sulphur and phosphorus agents. The other one was a conventional gear oil which didn't contain EP additives. A vibration switch was equipped near the gear box of test gears and could immediately switch off when an accident such as tooth breakage occurred. However, it hardly acted even though a pitting

Table 5 Properties of lubricants

	Density (g/cm^3)	Viscosity (mm^2/sec)		Viscosity index
		313K	373K	
Oil A	0.886	150	14.8	97
Oil B	0.877	63.3	8.57	107

Table 6 Numbers given to main experiments, heat treatment conditions, applied load, results of endurance test, etc.

No. of Exp.	Kind of test gear	Pattern of austemper treatment	Tangential load per face-width Fo/b (N/mm)	Revolutions of gear N ($\times 10^6$)	Test result
[1]	NGA	I	341	10.8	Non failure
[2]	NGA	I	391	0.85	Broken at tooth root
[3]	NGA	I	533	0.43	Broken at tooth root
[4]	NGB	I	391	10.8	Non failure
[5]	NGB	I	445	1.64	Broken at tooth filet
[6]	NGB	I	503	0.57	Broken at tooth filet
[7]	NGB	II	336	10.8	Non failure
[8]	NGB	II	391	1.69	Broken at tooth filet
[9]	NGB	II	445	2.07	Broken at tooth filet
[10]	NGB	II	503	0.75	Broken at tooth filet
[11]	SPN	I	341	10.8	Non failure
[12]	SPN	I	391	10.8	Non failure
[13]	SPN	I	418	10.8	Non failure
[14]	SPN	I	445	10.8	A little pitting
[15]	SPN	II	418	10.8	Non failure
[16]	SPN	II	445	5.40	Spalling failure
[17]	SPN	II	503	1.02	Broken at tooth filet
[18]	SPG	I	418	10.8	Non failure
[19]	SPG	I	503	0.71	Broken at tooth filet
[20]*	SPN	I	418	9.06	Broken at pitch point

*Resulted by using of conventional gear oil with no EP additives or a spalling failure occurred. Therefore, the endurance test had to be stopped manually hearing the noisy sound.

RESULTS AND DISCUSSION

Table 6 shows the numbers given to main experiments, patterns of heat treatment, results obtained by endurance tests, the position of breakage, etc. Most of results shown in Table 6 are also summarized in Fig.10.

Effects of shot peening on endurance limits : The gears shown in Exps.[1] to [10] for "NGA-Ⅰ", "NGB-Ⅰ" and "NGB-Ⅱ" were not performed shot peening after austemper treatments.

"NGA" group gears except Exp.[1], of which the tooth surface and tooth filet were finished by gear grinding after austemper treatment but tooth root was as-hobbed, were broken at tooth root finished by hobbing before austemper treatment as shown in Fig.11(a). The reason is thought that as-hobbed surface of tooth root is the rougher as shown in Fig.7 and decarburization is apt to be occurred there at elevated temperature for heat treatment. Additionally, it might be thought that the residual stress of tooth root is a little tension instead of compression in the positions of tooth filet and tooth surface as shown in Fig.9. The gear pair of "NGA-Ⅰ" group was, consequently, possible to rotate at the applied load of 341N/mm with no failure (Exp.[1]).

In order to improve the bending strength of ADI gears, the position of tooth root of "NGA" gears was additionally finished by the grinding. Although they corresponded to two gear groups of "NGB-Ⅰ" and "NGB-Ⅱ", the "NGB-Ⅰ" group gears had harder base hardness than those of "NGB-Ⅱ" group gears because of the lower austemper temperature. For the sake of additional grinding, the bending strength of the gears of "NGB-Ⅰ" increased more than those of "NGA-Ⅰ" (Exp.[4]). And it was broken down at tooth filet located to critical section of 30° of tooth which also corresponded to a site where the largest tensile stress was applied (shown in Fig.11(b)). In contrast to this, the bending strength of "NGB-Ⅱ" group gears seems to be hardly improvable (Exp.[7]). Though they might have had bending strength more than those of "NGB-Ⅰ" gears because they were tougher as shown in Table 2, they had consequently almost the same bending strength as those of "NGA-Ⅰ" gears.

The shot peened gears, termed "SPN", were examined to compare the endurance limits with the limits of the gears of no shot peening. When gear pairs of "SPN-Ⅰ" and "SPN-Ⅱ" were rotated under the applied load of 418 N/mm, they were possible to rotate through 10^7 revolutions(Exps.[13] and [15]). More-

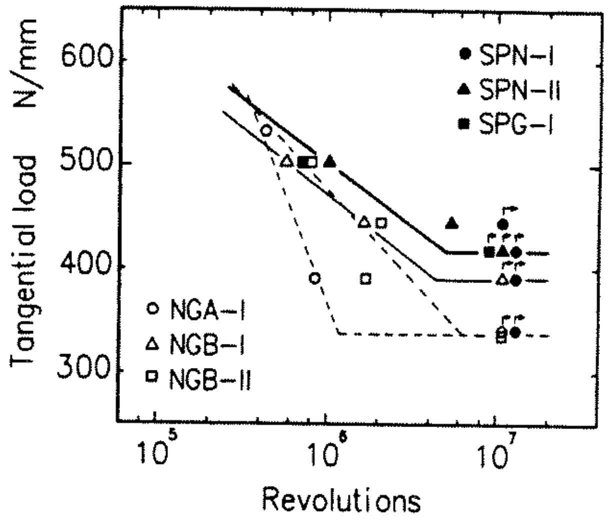
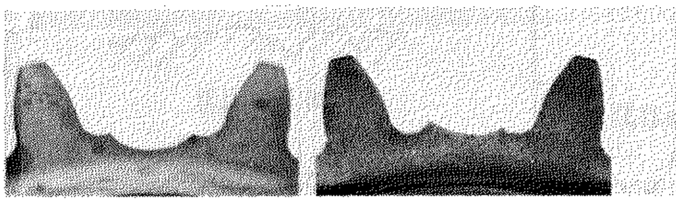


Figure 10 Results obtained by endurance tests



(a) Broken at tooth root (b) Broken at tooth filet

Figure 11 Gears broken by bending stress

Figure 12 Tooth surface damaged by spalling

over, they were rotated under the higher load of 445 N/mm. The gear pair of "SPN-Ⅰ" was permitted to rotate through 10^7 revolutions but some pitting were occurred and the accuracy of tooth profile near pitch point was slightly deteriorated (Exp.[14]). Otherwise, the gear pair of "SPN-Ⅱ" was manually stopped due to spalling failure occurred near pitch point after revolutions of 5.4×10^6 (Exp.[16]). The reason is thought that the "SPN-Ⅱ" group gears had lower hardness of 284HB than those of the "SPN-Ⅰ" group gears (365HB) obtained by austemper treatment Ⅰ as shown in Table 2. Fig.12 shows the spalling failure occurred in "SPN-Ⅱ" gear. Accordingly, it should be noted that the shot peened gears with the lower base hardness may be restricted by surface durabilities such as a pitting and/or spalling. In order to improve the bending strength and the surface durability simultaneously, "SPG" group gears were rotated. When a gear pair of "SPG-Ⅰ" was rotated under the applied load of 418 N/mm, the pair was possible to rotate through 10^7 revolutions (Exp.[18]). However, it was broken down by tooth breakage under the applied load of 503 N/mm (Exp.[19]).

From Exps.[13],[15] and [18], it is comprehensively understood that their endurance limits of "SPN-Ⅰ", "SPN-Ⅱ", and "SPG-Ⅰ" gear pairs were almost the same in each other, even though each fracture pattern was different when they were rotated under the higher applied loads. Consequently, the shot peening is effective to increase the endurance limits of the ADI gears. Especially, in comparison with the gears in the same manufacturing state before shot peening, endurance limits of shot peened gears was increased by 23% as shown in Exps.[1] and [13], respectively.

Shot peening bring about coarse surface roughness which is approximately twice those of ground gears, but it is cleared that shot peening is much effective to increase the endurance limits of the ADI gears. Changes in residual stresses of tooth filet after running are shown in Fig.13. From this figure, it is found that the compressive residual stress occurrs in only shallow layer below the surface of the ADI gears which are finished by grinding without shot peening. In case of shot peened gears heat-treated by austemper treatment Ⅰ, it was found that compressive residual stresses was almost same but deeper than that of the gears with no shot peening. And in another case of those heat-treated by austemper treatment Ⅱ, which had much retained austenite structure and lower hardness than those heat-treated by austemper treatment Ⅰ, it was found that compressive residual stress was a little less than but the same depth as those of austemper treatment Ⅰ.

The roughnesses of the tooth surface after running, in which any failure hardly occurred, are shown in Fig.14 (Exps.[13] and [15]). Even though shot peened gears have a coarse surface roughness, it is understood that surface roughnesses which had had a roughness of 5μm Rmax before running were improved due to effective running-in and then flattened the top of peek during the running.

The reason why the endurance limits of shot peened ADI gears was increased might be caused by the

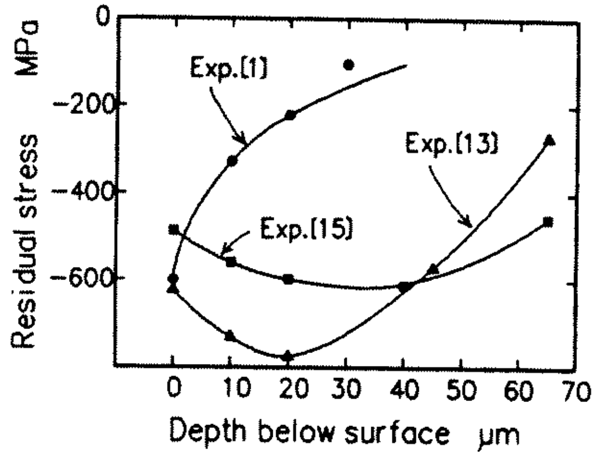


Figure 13 Changes in residual stresses of tooth filet after running

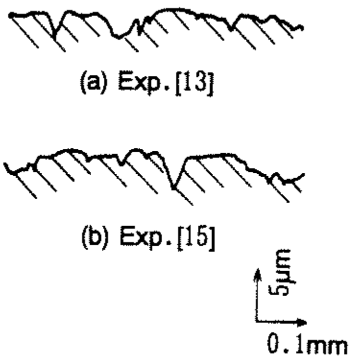


Figure 14 Changes in surface roughnesses of shot peened gears after running

deeper compressive residual stress and effective running-in.

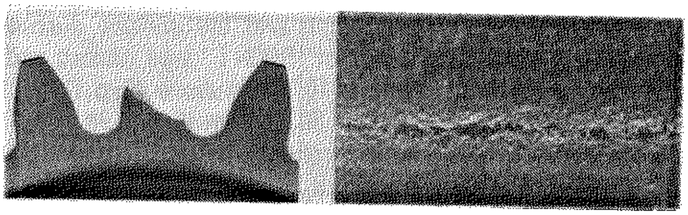


Figure 15 The tooth broken at pitch point and the tooth surface damaged by pitting after running in Exp.[20]

Effect of lubricants on endurance limit : Generally, it has been noted that endurance limits of the steel gears which had a hardness less than about 400Hv has been restricted by surface durability. The surface roughness of shot peened gears had a roughness of about 5μm Rmax. The severity of contact of meshing gear teeth has been assumed by the D-value shown in eq.(1).

$$D = h_{min} / (R_{max1} + R_{max2}) \quad (1)$$

where, R_{max1} and R_{max2} are the roughnesses of tooth surfaces of driver and driven gear, respectively. And h_{min} is theoretical oil film thickness derived by elasto-hydrodynamic lubrication (EHL) theory(5).
All of the aforementioned results are obtained by using the lubricant with EP additives of oil A which has larger viscosity than that of conventional lubricant without EP additives of oil B. Its theoretical oil film thickness of oil A is about 0.7μm at the temperature of 323K (=50°C). When the shot peened gears were combined as a test gear pair, the D-value was about 0.04. It was much smaller than a unity so that it might be assumed that sever metal contact was occurred.
Comparison examination to estimate the effect of lubricants on endurance limit was conducted by utilizing "SPN-Ⅰ" gears. When an oil A with EP additives was used (Exps.[13]), the gears was

rotated through 10^7 revolutions with no failure at applied load of 418N/mm. Then increasing the applied load to 445N/mm, it was also possible to rotate up to the same revolutions even though some pitting was occurred (Exp.[14]).
When oil B was used (Exp.[20]), the same gears were, in contrast to this, stopped by tooth breakage at pitch point before 10^7 revolutions in spite of less applied load than that in Exp.[14]. The broken tooth and the pitting failure occurred in other tooth surface of the gear are shown in Fig.15, respectively.
The theoretical oil film thickness using oil B was about $0.4\mu m$ at the temperature of 323 K (=50°C). Therefore, it was estimated that the D-value became less than 0.04 obtained by using oil A. It assumed that the tooth breakage, consequently, might be caused by pitting failure induced by insufficient running-in. In case that the ADI gears with coarse surface roughness by shot peening are applied to transmission gears, it is desired to use the oil with EP additives for the reduction of the severe metal contacts and the promotion of the effective running-in.

CONCLUSIONS

Effects of shot peening, austemper heat treatment and lubricants on endurance limits of ADI gears are comprehensively carried out by using a power circulating type gear endurance testing machine with the views of the bending strength and the surface durability. Following results are clarified.
(1) The shot peening brings about coarser surface roughness in ADI gears than that of conventional ground gears, but increases the endurance limit than that of the ground gears with no shot peening.
(2) The deeper compressive residual stress layer induced below the surface of tooth filet of ADI gears by shot peening is effective to increase the bending strength more than the shallow compressive residual stress layer induced by grinding.
(3) Shot peening scarcely deteriorates the accuracies of ADI gears and brings about almost the same endurance limits in ADI gears as those of the precise shot-peened gears of which tooth surface was finished by gear grinding.
(4) When base metal hardness is low, the endurance limit of shot peened ADI gears is restricted by pitting and/or spalling failure.
(5) In running the shot peened ADI gears with coarse surface roughness, it is effective to use the lubricants with EP additives for the reduction of the damages by severe metal contact, promotion of the effective running-in and the improvement of the surface durability .

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