A Fundamental Study of the Surface Durability of Medium-Hardness Gears*

(Effects of Combination of Hardness and Surface Roughness)

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The effects of the combination of tooth flank hardness and tooth surface roughness on the surface durability of medium-hardness gears are investigated using a disk machine. The meaning of the difference in hardness between a pair of gears is discussed. In the case where the surface roughnesses differ between contact surfaces with the same initial hardness, severe wear and pitting occur on the smooth surface because the asperities on the rough surface are highly hardened due to the repetition of contact. Therefore, it is necessary that the initial hardness of the smooth surface is higher than that of the rough surface in a combination of different surface roughnesses. This means that the hardness combination between a pair of gears should be determined in consideration of the final condition of the finished tooth surfaces of the gears.

Key Words: Gear, Medium-Hardness Gears, Surface Durability, Hardness, Surface Roughness, Pitting, Wear, Work Hardening, Disk Machine

1. Introduction

Usually, the hardnesses of medium-hardness gears, which are often used in medium- or large-size gear units, differ between a pair of gears. For the hardness combination of gears, there are many cases where the pinion is made harder than the gear in the expectation of an increase of the surface durability of the gear due to a work-hardening effect. The work-hardening effect is considered in design formulas such as the AGMA⁽¹⁾ and the ISO⁽²⁾.

On the other hand, for surface durability in medium-hardness (hardened and tempered) steels, when the initial hardnesses differ between the contact surfaces, it is clarified that the initial surface roughness of the harder surface has much influence on the pitting resistance of the softer surface⁽³⁾. In addition,

when the initial surface roughnesses are large ($6\sim 10\ \mu\text{m } R_{\text{max}}$), it is clarified that the larger the difference in hardness is, the lower the pitting resistance of the softer surface becomes⁽⁴⁾. These facts show that the combination of initial hardness and surface roughness has much influence on the surface durability. However, the influences of the combination of hardness and surface roughness in practical use have not been sufficiently clarified. Therefore, the effects of the combination of hardness and surface roughness on the surface durability are not specified in design formulas such as the AGMA⁽¹⁾ and the ISO⁽²⁾.

In this paper, the effects of hardness and roughness combination on the surface durability are investigated systematically using a disk machine which simulates the rolling/sliding contact motion between surfaces of working gear teeth. On the Basis of the results, the meaning of the difference in hardness between a pair of gears are discussed.

2. Experimental Conditions and Method

2.1 Test rollers and material

The chemical composition and the dimensions of the test rollers are shown in Table 1 and Fig. 1, respec-

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tively. The test rollers are finished by cylindrical grinding after heat treatment (See Table 3).

2.2 Simulation of contact of rollers to that of gears

The pitting of gears most often occurs on the dedendum near the pitch line, where there is one pair of teeth in contact under the condition of a negative slide/roll ratio. When the tooth flank hardness or conditions of the finished tooth surfaces differ between a pair of gears, the changes in the number of pits against the number of cycles also differ between them^{(5),(6)}. Therefore, when the effects of the combination of initial hardness and tooth surface roughness on the surface durability are examined using a disk machine, it is necessary to simulate both situations in which the dedendum of pinion tooth engages the addendum of gear tooth (See Fig. 2(a)) and the addendum of pinion tooth engages the dedendum of gear tooth (See Fig. 2(b)).

2.3 Roller test apparatus, lubricant and test method

The test apparatus is a 2-roller-type contact fatigue testing machine⁽⁷⁾. The rolling/sliding conditions are shown in Table 2.

The lubricant is SAE 30 base oil [specific gravity

Table 1 Chemical composition of test material

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo
Cr-Mo steel (JIS SCM435)	0.34	0.31	0.67	0.021	0.014	0.01	0.03	0.95	0.18

Fig. 1 Dimensions of test rollers

Fig. 2 Simulation of contact of rollers to gears

0.8848 (288/277 K), viscosity $98.32 \times 10^{-6} \text{ m}^2/\text{s}$ (313 K), $11.19 \times 10^{-6} \text{ m}^2/\text{s}$ (373 K)] and is supplied above the contact zone of the roller set by an oil jet. The inlet oil temperature is adjusted to $313 \pm 2 \text{ K}$ and the oil flow rate is held constant at $33 \times 10^{-6} \text{ m}^3/\text{s}$. The calculated EHD film thickness $h_{\min}^{(8)}$ is $3.4 \sim 2.2 \mu\text{m}$ (oil temperature 313 K) and $0.8 \sim 0.5 \mu\text{m}$ (373 K) under conditions of maximum Hertzian stress $\sigma_H = 290 \sim 1570 \text{ MPa}$.

In order to evaluate the surface durability, the appearances of contact surfaces are observed and the surface roughness is measured at suitable intervals.

3. Experimental Results and Discussion

3.1 Experimental conditions and results

The experimental results are shown in Table 3. The values of $1 \mu\text{m}$ and $10 \mu\text{m}$ $R_{\max}$ correspond to the tooth surface roughness of the ground gears and hobbed gears, respectively⁽⁹⁾. Pits occur mostly on the lower speed roller within the limits of these experimental conditions.

3.2 Effects of hardness and surface roughness combination on the pitting resistance

3.2.1 Effects of surface roughness combination

Figure 3 shows the changes in the number of pits (Diameter $\geq 0.3 \text{ mm}$) against the number of cycles in the higher speed roller N_1 , when the initial hardnesses are almost the same between a pair of rollers. In this study, the pitting life is defined as the number of cycles

Table 2 Rolling/sliding conditions of roller test

	Lower speed roller (L)	Higher speed roller (H)
Speed of rotation rpm	2630	3190
Peripheral speed m/s	9.36	11.36
Specific sliding %	-21	17
Sliding velocity m/s	2.0

Fig. 3 Changes in number of pits (Diameter $\geq 0.3 \text{ mm}$) ($\Delta\text{HB} \approx 0$, $\sigma_H = 1370 \text{ MPa}$)

when the first pit (Diameter ≥ 0.3 mm) occurs. The pitting life is obtained by an extrapolation of the curve that is plotted from the number of pits against the number of cycles N_1 because the curve almost

becomes a straight line.

Figure 4 shows the σ_H - N_1 curves for pitting in lower speed rollers. In Fig. 4, σ_H is the maximum Hertzian stress, and N_1 is the number of cycles when the first pit occurs. When the initial hardnesses are almost the same, but the initial surface roughnesses differ between a pair of rollers, the pitting life of the rollers with a smooth surface ($1 \mu\text{m } R_{\text{max}}$) is always shorter than that with a rough surface ($10 \mu\text{m } R_{\text{max}}$) at the same Hertzian stress. The results are similar to the results of gear tests in which severe pitting occurred on the tooth surfaces of the pinion when the ground pinion was meshed with a hobbled gear of the same initial hardness⁽⁶⁾.

Figure 5 shows the effect of the surface roughness combination on the pitting limits in a case of the same initial hardness. Pairs of rollers with a combination of the surface roughness of $1 \mu\text{m}$ and $10 \mu\text{m } R_{\text{max}}$ have pitting limit of about 0.26 HB kgf/mm^2 , while the pitting limit of pairs of rollers with $10 \mu\text{m } R_{\text{max}}$ is about 0.1 HB kgf/mm^2 . Namely, the results indicate that a remarkable improvement of the pitting limit can be expected by finishing the tooth surface of one

Fig. 4 σ_H - N_1 curves

Table 3 Experimental conditions and results

Test No.	Hardness HB			Surface roughness						Rmax μm		Max Hertzian stress σ _H		σ _w HB	Cycles run in H	Number of pits in L (at N ₁)		
				Approx. value		Initial		Final								φ0.1 ~φ0.2	φ0.3 ~φ0.9	φ1.0~
	L*1	H*2	ΔHB	L	H	L	H	L	H	MPa	kgf/mm ²	(kgf/mm ²)	N ₁					
A - 1	348	348	0	1	1	1.2	1.7	0.5	0.9	1570	160	0.46	3.4×10 ⁵	11	3	10		
A - 2	345	345				1.1	1.4	0.3	1.0	1370	140	0.41	4.4×10 ⁵	10	0	3		
A - 3	343	343				1.2	1.4	0.4	0.9	1280	130	0.38	6.6×10 ⁵	17	5	6		
A - 4	341	341				1.0	1.2	0.6	0.7	1180	120	0.35	10 ⁷	0	0	0		
A - 5	341	342				1.2	1.3	0.8	0.7	1470	150	0.44	10 ⁷	2	0	0		
A - 6	346	346				1.5	1.5	0.8	0.8	1370	140	0.40	10 ⁷	2	0	0		
A - 7	346	346				1.1	1.2	0.6	0.8	1370	140	0.40	10 ⁷	1	0	0		
A - 8	348	435	85 ~88	1	1	1.2	1.5	0.4	1.1	1470	150	0.43	1.7×10 ⁶	1	2	5		
A - 9	344	432				1.2	1.2	0.4	0.9	1370	140	0.41	1.1×10 ⁶	20	6	5		
A - 10	342	427				1.3	1.6	0.5	1.1	1280	130	0.38	10 ⁷	12	5	1		
A - 11	348	435				1.1	1.1	0.5	0.9	1180	120	0.34	10 ⁷	0	0	0		
B - 1	318	318	0	10	10	8.7	12.0	3.8	5.1	1670	170	0.53	10 ⁵	2	1	1		
B - 2	315	316				6.8	9.7	1.5	5.3	1370	140	0.44	3.4×10 ⁵	2	1	2		
B - 3	319	319				9.0	9.3	4.0	3.7	980	100	0.31	7.8×10 ⁵	0	2	1		
B - 4	317	317				8.3	6.7	6.2	6.0	490	50	0.16	7.0×10 ⁵	>25	1	0		
B - 5	317	317				9.3	7.2	8.2	5.8	290	30	0.10	10 ⁷	many	1	0		
C - 1	345	345	0	1	10	1.0	8.2	2.2	4.4	1370	140	0.41	6.0×10 ⁵	25	4	8		
C - 2	349	348				1.0	10.3	2.9	5.4	1180	120	0.34	2.2×10 ⁶	11	9	3		
C - 3	343	343				1.0	9.6	2.0	6.1	980	100	0.29	4.2×10 ⁶	0	2	4		
C - 4	342	342				1.1	10.2	1.7	5.9	880	90	0.26	10 ⁷	0	0	1		
C - 12	344	342				1.5	10.9	2.6	6.3	1370	140	0.41	10 ⁶	—	—	—		
C - 13	344	343				1.1	9.4	2.4	5.3	1370	140	0.41	10 ⁵	—	—	—		
C - 14	344	344				1.7	9.9	2.0	7.0	880	90	0.26	10 ⁶	—	—	—		
C - 15	343	342				1.4	8.4	2.2	6.1	880	90	0.26	10 ⁵	—	—	—		
C - 5	386	344				42	1	10	1.2	9.9	1.8	4.3	1370	140	0.36	10 ⁶	5	3
C - 9	430	345	85	1	10	1.3	8.4	1.1	2.9	1570	160	0.37	6.5×10 ⁶	8	2	4		
C - 10	428	343				1.3	9.2	0.8	3.9	1370	140	0.33	8.0×10 ⁶	>100	10	2		
C - 11	423	338				1.3	9.7	1.2	3.9	1180	120	0.28	10 ⁷	5	0	0		
D - 1	348	347	0	10	1	8.3	1.1	3.6	1.8	1570	160	0.46	1.3×10 ⁶	57	4	4		
D - 2	346	345				9.4	1.2	4.2	0.6	1370	140	0.41	3.3×10 ⁶	many	10	3		
D - 3	348	348				10.5	1.3	6.3	3.3	1180	120	0.34	6.0×10 ⁶	64	6	0		
D - 4	343	343				8.7	1.0	5.1	2.9	980	100	0.29	10 ⁷	0	0	0		
D - 11	343	428	82 ~87	10	1	9.3	1.5	3.4	1.2	1370	140	0.41	2.3×10 ⁵	0	7	4		
D - 12	344	431				14.0	1.4	5.5	1.3	1370	140	0.41	10 ⁷	38	6	1		
D - 13	337	419				9.2	1.1	4.0	1.1	1180	120	0.36	3.0×10 ⁶	25	11	2		
D - 14	346	433				8.6	1.5	4.7	0.8	1080	110	0.32	10 ⁷	34	4	0		
D - 15	346	430				8.1	1.0	5.2	1.2	980	100	0.29	10 ⁷	0	0	0		
D - 16	342	427				8.4	1.2	5.6	1.4	980	100	0.29	10 ⁷	8	1	0		
D - 17	344	429				9.4	1.5	4.8	1.0	780	80	0.23	10 ⁷	19	1	0		

*1 Lower speed roller

*2 Higher speed roller

of the gears in a pair of gears.

3.2.2 Effects of hardness and surface roughness combination The effect of the combination of hardness and surface roughness on the pitting limits is shown in Fig. 6. The smaller value between the pitting limits of two combinations where two rollers with fixed initial hardness and surface roughness replace each other at the lower speed side and the higher speed side, is equivalent to the endurance limit of a pair of gears. When the surface roughnesses differ between a pair of rollers, upon increasing the initial hardness of the roller with a smooth surface, compared with that with a rough surface, within the difference in hardness $\Delta HB \approx 40$, the equivalent endurance limit increases. In a case of the same surface roughness ($1 \mu\text{m } R_{\text{max}}$) combination, if the initial hardness of only one roller of the pair increases, the equivalent endurance limit decreases because of the decrease in the pitting limit of the softer roller.

With reference to the effects of the surface roughness combination on the surface durability, when the pinion is made harder than the gear, only the effect of the tooth surface roughness of the pinion is taken into account in design formulas such as the AGMA⁽¹⁾ and the ISO⁽²⁾. However, when the tooth surfaces of both gears are finished smoothly, there is a possibility of a decrease in the surface durability compared with the case of the same hardness combination. Namely, the

Fig. 5 Effect of surface roughness combination on pitting limits⁽⁷⁾ ($\Delta HB \approx 0$)

Fig. 6 Effect of hardness and surface roughness combination on pitting limits⁽¹⁰⁾

results indicate that an improvement of surface durability due to the difference in hardness can be expected in the case where the tooth surface roughnesses differ between a pair of gears. Furthermore, in the above case, it is necessary for the pinion with smooth surfaces to be harder than the gear with rough surfaces, in order to improve the surface durability of the pinion rather than the gear.

3.3 Effects of the surface roughness combination on the surface failure

For the combination of a lower speed roller with a surface roughness of $1 \mu\text{m } R_{\text{max}}$ and a higher speed roller with $10 \mu\text{m } R_{\text{max}}$, with the same initial hardness, the profiles of the contact surface before and after running until $N_1 = 10^4$ and 10^7 cycles are shown in Fig. 7, and Fig. 8 shows scanning electron microscopy (SEM) photographs of the contact surface after running. The roller with $1 \mu\text{m } R_{\text{max}}$ is considerably worn out, as shown in Fig. 7. The results are similar to the results of gear tests in which severe wear occurred on the tooth surfaces of the pinion when the ground pinion was meshed with a hobbed gear with the same initial hardness⁽⁶⁾. The wear of the roller with $1 \mu\text{m } R_{\text{max}}$ progresses rapidly at an earlier stage of running, but after that, the progress slows with the number of cycles⁽¹¹⁾. In Fig. 8, grooves ploughed by the asperities on the roller with $10 \mu\text{m } R_{\text{max}}$ are observed on the contact surface of the roller with $1 \mu\text{m } R_{\text{max}}$ after running until $N_1 = 10^4$ cycles. The asperities on the rough surface become flat with the number of cycles, and the mating surface of the roller with $1 \mu\text{m } R_{\text{max}}$ becomes smooth.

Fig. 7 Profiles of contact surface before and after running ($\Delta HB \approx 0$, $L: 1 \mu\text{m } R_{\text{max}}$, $H: 10 \mu\text{m } R_{\text{max}}$, $\sigma_H = 880 \text{ MPa}$)

Figure 9 shows the hardness distributions of the lower speed roller measured near the contact surface after running, in the case of the different surface roughness combination. There is a considerably work-hardening portion near the surface of the roller with $1\text{ }\mu\text{m}$ R_{max} compared with the roller with $10\text{ }\mu\text{m}$ R_{max} .

The changes in the surface roughness and the surface hardness against the number of cycles are shown in Figs. 10 and 11, respectively. In Fig. 10, the surface roughness of the roller with a rough surface decreases at an earlier stage of running. In Fig. 11, the

surface hardness is measured for a small area of the asperities with a small load (0.015 kgf). The non-contact surface hardness values of the roller with $1\text{ }\mu\text{m}$ and $10\text{ }\mu\text{m}$ R_{max} are HV380~430 and HV390~460, respectively. When the wear of the roller with $1\text{ }\mu\text{m}$ R_{max} progresses rapidly at an earlier stage of running ($N_1=10^4$), highly hardened areas exist on the roller with $10\text{ }\mu\text{m}$ R_{max} compared with the roller with $1\text{ }\mu\text{m}$ R_{max} . On the other hand, when the wear of the roller with $1\text{ }\mu\text{m}$ R_{max} hardly progresses ($N_1=10^7$), the surface of the roller with $1\text{ }\mu\text{m}$ R_{max} is harder than the roller with $10\text{ }\mu\text{m}$ R_{max} . These facts indicate that the wear of the smooth surface is caused by the asperities on the mating rough surface that are highly hardened due to the repetition of contact⁽¹²⁾. Furthermore, it is considered that the severe pitting on the roller with a smooth surface occurs because the surface is subjected to plastic deformation by the highly hardened asperities on the mating rough surface. Therefore, in

Fig. 8 SEM photographs of contact surface after running ($\Delta\text{HB}\approx 0$, $L: 1\text{ }\mu\text{m}$ R_{max} , $H: 10\text{ }\mu\text{m}$ R_{max} , $\sigma_H=880\text{ MPa}$)

Fig. 9 Sectional hardness distribution ($\Delta\text{HB}\approx 0$)

Fig. 10 Changes in surface roughness ($\Delta\text{HB}\approx 0$, $L: 1\text{ }\mu\text{m}$ R_{max} , $H: 10\text{ }\mu\text{m}$ R_{max} , $\sigma_H=880\text{ MPa}$)

Fig. 11 Changes in surface hardness ($\Delta\text{HB}\approx 0$, $L: 1\text{ }\mu\text{m}$ R_{max} , $H: 10\text{ }\mu\text{m}$ R_{max} , $\sigma_H=880\text{ MPa}$)

the case of the different surface roughness combination, it is essential that the initial hardness of the smooth surface is higher than that of the rough surface.

3.4 Effects of hardness and surface roughness combination on the surface failure

For the combination of a lower speed roller with a surface roughness of $1\text{ }\mu\text{m } R_{\text{max}}$ and a higher speed roller with $10\text{ }\mu\text{m } R_{\text{max}}$, the profiles of the contact surface before and after running, and the hardness distributions measured near the contact surface after running, are shown in Figs. 12 and 13, respectively. In the case of $\Delta\text{HB} \approx 85$, the roller with $1\text{ }\mu\text{m } R_{\text{max}}$ is hardly worn, as shown in Fig. 12, and it is found that the wear of the roller with a smooth surface can be

Fig. 12 Profiles of contact surface before and after running
($L: 1\text{ }\mu\text{m } R_{\text{max}}$, $H: 10\text{ }\mu\text{m } R_{\text{max}}$, $\sigma_H = 1\text{ }370\text{ MPa}$)

Fig. 13 Sectional hardness distribution
($L: 1\text{ }\mu\text{m } R_{\text{max}}$, $H: 10\text{ }\mu\text{m } R_{\text{max}}$, $\sigma_H = 1\text{ }370\text{ MPa}$)

prevented by the difference in hardness between a pair of rollers.

In the cases of $\Delta\text{HB} \approx 40, 85$, work hardening near the surface of the rollers with $1\text{ }\mu\text{m } R_{\text{max}}$ does not occur as much as in the case of $\Delta\text{HB} \approx 0$. The effect of the initial hardness combination on the increase in surface hardness due to the repetition of contact is shown in Fig. 14. The amount of the increase in surface hardness is obtained from the difference in hardness (load 1 kgf) between the contact and the non-contact surface. When the surface roughnesses differ between a pair of rollers with the same initial hardness, it is clear that the higher the initial hardnesses of a pair of rollers, the more remarkable the effects of the surface roughness combination on the occurrence of pitting are, and the smooth surface with the initial hardness HB 425 also work-hardens after running, as in the case of HB 300^{(13),(14)}. In Fig. 14, compared to the initial hardness of the roller with the rough surface, the higher that of the roller with the smooth surface is, the smaller the amount of the increase in surface hardness with the smooth surface is. This result indicates that damage of the smooth surface can be decreased by the difference in hardness.

In the case of the combination of a lower speed roller with $10\text{ }\mu\text{m } R_{\text{max}}$ and a higher speed roller with $1\text{ }\mu\text{m } R_{\text{max}}$, the profiles of the contact surface before and after running and the hardness distributions measured near the contact surface after running, are shown in Figs. 15 and 16, respectively. In the case of $\Delta\text{HB} \approx 85$, the changes in the surface roughness and the increase in surface hardness of the roller with $10\text{ }\mu\text{m } R_{\text{max}}$ become larger than those in the case of $\Delta\text{HB} \approx 0$. These results reveal that damage of the roller with the rough surface (HB345, $10\text{ }\mu\text{m } R_{\text{max}}$) increases due to the increase in initial hardness of the mating roller with the smooth surface ($1\text{ }\mu\text{m } R_{\text{max}}$).

For the same roughness ($1\text{ }\mu\text{m } R_{\text{max}}$) combination, the profiles of contact surface before and after running and the hardness distributions measured near the

Fig. 14 Effect of initial hardness combination on increase in surface hardness
($L: 1\text{ }\mu\text{m } R_{\text{max}}$, $H: 10\text{ }\mu\text{m } R_{\text{max}}$, $\sigma_H = 1\text{ }370\text{ MPa}$)

Fig. 15 Profiles of contact surface before and after running
($L: 10 \mu\text{m } R_{\text{max}}$, $H: 1 \mu\text{m } R_{\text{max}}$, $\sigma_H = 1370 \text{ MPa}$)

Fig. 16 Sectional hardness distribution
($L: 10 \mu\text{m } R_{\text{max}}$, $H: 1 \mu\text{m } R_{\text{max}}$, $\sigma_H = 1370 \text{ MPa}$)

contact surface after running are shown in Figs. 17 and 18, respectively. In the case of $\Delta HB \approx 0$, no pitting occurs at $\sigma_H = 1370 \text{ MPa}$ and the surfaces of a pair of rollers become equally smooth after running. On the other hand, in the case of $\Delta HB \approx 88$, the surface roughness of the harder roller changes a little, whereas the surface of the softer roller (lower speed roller HB 345) in which the pitting occurs becomes considerably smooth and the surface work-hardens markedly compared with the lower speed roller (HB 345) in the case of $\Delta HB \approx 0$. From the above results, it is considered that the surface of the softer roller is damaged by the asperities of the harder roller because the surface roughness of the harder roller is hardly reduced in the case of $\Delta HB \approx 85$; consequently, pitting occurs earlier on the softer roller than in the case of $\Delta HB \approx 0$.

Fig. 17 Profiles of contact surface before and after running
($L: 1 \mu\text{m } R_{\text{max}}$, $H: 1 \mu\text{m } R_{\text{max}}$, $\sigma_H = 1370 \text{ MPa}$)

Fig. 18 Sectional hardness distribution
($L: 1 \mu\text{m } R_{\text{max}}$, $H: 1 \mu\text{m } R_{\text{max}}$, $\sigma_H = 1370 \text{ MPa}$)

4. Conclusions

The effects of the combination of hardness and surface roughness on the surface durability in medium-hardness steel are investigated using a disk machine, and the meaning of the difference in hardness between a pair of gears is discussed.

When the surface roughnesses differ between contact surfaces with same initial hardness, severe pitting and wear occur on the smooth surface. It is thought that the pitting and wear are caused by the highly hardened asperities on the rough surface due to the repetition of contact. Therefore, it is necessary that the initial hardness of the smooth surface is higher than that of the rough surface in order to improve the surface durability. However, an excessive difference in hardness increases damage of the softer roller with a rough surface.

On the other hand, in the case of the combination

of different hardness and same surface roughness, the surface of the softer roller is damaged by the asperities of the harder roller and the pitting limit reduces compared with the pitting limit of the same hardness combination.

From the above results, the following are concluded:

(1) An improvement of surface durability by a difference in hardness between a pair of gears can be expected when their tooth surface roughnesses are different and it is necessary for the pinion with smooth surfaces to be harder than the gear with rough surfaces, in order to improve the surface durability of the pinion rather than the gear.

(2) Furthermore, it is necessary that an appropriate difference in hardness is given between a pair of gears because an excessive difference in hardness increases damage of the softer gear with rough surfaces.

(3) Namely, when the improvement of surface durability by difference in hardness between a pair of gears is attempted, the hardness combination of a pair of gears should be determined in consideration of the final condition of the finished tooth surfaces of the gears.

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