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Surface Durability of Steel Rollers* (In Relation to Hardness)

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In order to clarify the effects of hardness on the surface durability and surface failure, fatigue tests on various heat-treated steel rollers were carried out under sliding rolling contact condition.

The surface failure modes could be estimated by the values of the maximum amplitudes A_{max} of the ratios of normal stress on the surface in circumferential direction of roller and of orthogonal shear stress under the surface to Vickers hardness and the peak amplitude A_{peak} of the ratio of orthogonal shear stress to Vickers hardness which occurs at case-core boundary.

The relation between the surface durability together with the surface failure mechanism and the hardness distribution could be clarified by calculating the amplitudes A_{max} and A_{peak} and by Vickers hardness at the depth of these amplitudes. From the standpoint of design, the surface durability of a machine element can be evaluated from the equation $A_{max} = 0.051$ or $A_{peak} = 0.035$ when the hardness and residual stress distributions of the machine element are known.

1. Introduction

Various heat-treated steels are used as power transmission gear materials and gear materials with various hardnesses are selected corresponding to gear load and operating condition such as load carrying capacity. Investigated results on surface durability of these gear materials with various hardnesses have been reported⁽¹⁾⁻⁽³⁾. On the other hand, effect of hardness on surface failure modes and mechanisms has not been so clear. Therefore, it can be considered that the relationship between the surface durability and the hardness must be discussed considering surface failure modes and mechanisms.

The authors have investigated on the surface durability and the surface failure of annealed⁽⁴⁾ ⁽⁵⁾ and thermally refined⁽⁵⁾ 0.45 percent carbon steel rollers with Hv180 to 300, and of induction-hardened 0.45 percent carbon steel⁽⁶⁾, case-hardened nickel chromium steel⁽⁷⁾ and nitrided aluminium chromium molybdenum steel⁽⁸⁾ rollers with Hv746 to 1220. However, in order to discuss the surface durability and the surface failure concerning hardness, the investigations about the rollers with such a range of hardnesses that the surface failure mode may change from pitting to spalling are required.

Therefore, in this report, in order to investigate the relationship between the surface durability of practical gear materials and the hardness concerning the mechanism of surface failure, thermally

refined and through hardened 0.45 percent carbon steel rollers with Hv333 to 728 were tested in supplementary experiments and the surface failure and surface durability of these rollers were clarified. From these supplementary and previous⁽⁴⁾ ⁽⁵⁾ ⁽⁶⁾ ⁽⁷⁾ ⁽⁸⁾ results, the relationship between surface durability and hardness was discussed and summarized. And it was made clear that the surface durability must be evaluated by the hardness at initiation depth of surface failure.

2. Supplementary experiments

2.1 Roller specimens and experimental procedures

Materials used in these experiments are 0.45 percent carbon steel S45C and nickel chromium steel SNC21 of which chemical compositions are the same ones as reported in previous report⁽⁶⁾. An S45C steel bar was machined to rollers and then thermally refined rollers TA and TB and through hardened rollers Q were obtained after heat treatments as shown in Table 1. An SNC21 steel bar was turned to predetermined diameter, carburized and then was machined to rollers and a case-hardened roller C was obtained after quenching and tempering under the condition shown in Table 1. All these rollers were finished by grinding to surface roughness of about $1 \mu m R_{max}$. The shapes

Table 1 Specimens and heat treatments

Specimen mark	Roller material	Heat treatment
TA	Thermal-refined S45C	Quenching : 900°Cx1h WQ Tempering : 560°Cx1h WC
TB		Quenching : 900°Cx1h WQ Tempering : 400°Cx1h WC
Q	Through-hardened S45C	Quenching : 900°Cx1h WQ Tempering : 175°Cx2h AC
C	Case-hardened SNC21	Carburizing : 930°Cx6.5h, 800°Cx0.5h FC Primary quenching : 875°Cx1h OQ Secondary quenching : 800°Cx1h WQ Tempering : 175°Cx2h AC

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and dimensions of rollers are the same as described in previous report⁽⁷⁾ and diameter of the rollers is 60 mm. Width of roller specimens TA, TB and Q is 5 mm and that of mating rollers C is 10 mm.

Fig.1 Hardness distributions of roller specimens

Fig.2 Residual stress distributions of roller specimens

The hardness distributions of roller specimens are shown in Fig.1. Hardnesses of all rollers are maximum at surface and surface hardnesses of roller specimens TA, TB and Q are Hv333, 560 and 728 respectively. Fig.2 shows the residual stress distributions of roller specimens. The measuring and modifying methods of residual stress are the same as described in previous report⁽⁷⁾. Taking an origin at the center of width on roller surface, the coordinates x , y and z were taken in axial, circumferential and radial directions of roller, respectively. In surface layer of all roller specimens, the residual stresses $(\sigma_x)_r$ in axial direction and $(\sigma_y)_r$ in circumferential direction are compressive and the shapes of these compressive residual stress distributions agree qualitatively with the shapes of hardness distributions shown in Fig.1. The hardness and residual stress distributions of roller specimen C are shown in previous report⁽⁶⁾. Surface hardness and effective case depth of specimen C are Hv860 and about 1.1 mm respectively.

Fatigue tests were performed under sliding rolling contact condition by using a spring loading type rolling contact fatigue testing machine. Rotating speed

and circumferential velocity of the higher speed roller are 1790 rpm and 5.62 m/s, and those of the lower speed one are 1424 rpm and 4.47 m/s respectively. The rolling and sliding directions of the higher speed roller are the same and those of the lower speed one are opposite to each other. Thus, the specific sliding is +20.5% on the higher speed roller and -25.7% on the lower speed one. In these experiments, the roller specimens TA, TB and Q were taken as the lower speed rollers and the mating roller specimens C were taken as the higher speed rollers. The turbine oil 83 was fed to the ingoing side of contact position at a rate of 140 ml/min with pressure and the oil temperature was adjusted to $40 \pm 4^\circ\text{C}$. In these experiments, the minimum thickness of oil film by D. Dowson⁽⁹⁾ was in the range of 1.23 to 1.45 μm and D-value by P. H. Dawson⁽¹⁰⁾ was 1.38 to 1.63.

2.2 Experimental results

Figure 3 shows the relationships between Hertzian stress P_{max} and number of cycles to failure N for each roller specimen. The surface failure mode of specimen TA was pitting and that of the other specimens was pitting and spalling. Fatigue life was defined as the number of cycles when the percentage of pitted area reached 3% in the case of specimen TA and as the number of cycles when the test rig was automatically stopped by an increase in vibration due to the formation of a spall or several pits in the case of the other specimens. The rolling contact fatigue life of specimen TA is the shortest followed by specimens TB and Q. The surface durabilities for 10^7 cycles are 95, 100 and 135 kg/mm^2 for specimens TA, TB and Q respectively. The surface durability increases with an increase in hardness at surface layer of roller.

Figure 4 shows typical examples of fracture surfaces on the left hand side and microphotographs in transverse sections of the same specimens on the right hand side.

A pit formed on specimen TA is shown in Fig.4(a) and it can be said that the pit was formed by a surface-originated pitting crack which propagated inwards and in the rolling direction of roller⁽⁴⁾ (5). The pits formed under other Hertzian stresses were similar to ones in Fig.4(a). Fig.4(b) shows a spall formed on specimen TB. It can

Fig.3 P_{max} - N curves

be considered from this figure that the spalling crack occurred beneath roller surface and propagated parallel to the surface, and then the surface layer was torn away. In the case of specimen TB pits also occurred and the appearance of these pits is similar to that in Fig.4(a). Fig.4(c) and (d) show the spall-like pits and the spall on specimen Q respectively. In Fig. 4(d), several secondary cracks from the parallel spalling crack beneath the roller surface to the surface are observed. This indicates that the spall is formed after these secondary cracks reach the surface.

Table 2 shows the depth of surface failure formed on each specimen. In this experimental range, the depths of pit and spall are little influenced by the differences in specimen and Hertzian stress, and the maximum depths of pits are 0.4 to 0.9 mm and the spall depths are 0.2 to 0.5 mm. It can be considered from the observation result of Fig.4 and previous report(7) that the initiation depths of spalling cracks lie between the minimum and maximum depths of spalls shown in Table 2.

Fig.4 Surface failures and their transverse sections

Table 2 Depths of surface failures

pmax kg/mm²	Depth of surface failure mm			
	T A		T B	Q
	Min. - Max.	Min. - Max.	Min. - Max.	Min. - Max.
100	P 0.37	—	—	—
110	P 0.51	0.19 - 0.49	—	—
120	P 0.91	0.24 - 0.56	—	—
130	P 0.63	P 0.50	0.18 - 0.42	—
140	—	0.20 - 0.47	0.17 - 0.50	—
150	—	P 0.62	0.28 - 0.56	—
160	—	—	P 0.51	—
170	—	—	P 0.54	—

Letter P indicates pitting failure and the others spalling failure. In case of pitting failure the maximum depths of pits only are given.

2.3 Discussion

Assuming that the strength of a material is proportional to its hardness, it can be considered that fatigue cracks will occur when the amplitude of the ratio of stress to hardness which takes account of the distributions of hardnesses and residual stresses of specimen exceeds the critical value since the pitting or spalling is a kind of fatigue failure.

Normal stress σ and shear stress τ distribute in roller under sliding rolling contact. Simplifying the problem as described in previous report(5), it can be considered that the amplitudes $A(\sigma/\sqrt{3}Hv)$ and $A(\tau/Hv)$ are equivalent to each other for surface failure and give basis to discuss the surface failure and the surface durability.

Figures 5, 6 and 7 show examples of the distributions of these amplitudes. Table 3 shows the maximum values of these amplitudes, the depths of these maximum amplitudes and the hardnesses of these depths. The

Fig.5 Distributions of amplitudes $A(\tau/Hv)$ and $A(\sigma/\sqrt{3}Hv)$

Fig.6 Distributions of amplitudes $A(\tau/Hv)$ and $A(\sigma/\sqrt{3}Hv)$

stress beneath roller surface was calculated by using the analytical method after J. O. Smith⁽¹¹⁾, assuming that coefficient of friction μ of roller pair is 0.05⁽¹²⁾, modulus of longitudinal elasticity E is 21000 kg/mm² and Poisson's ratio ν is 0.3.

In calculation of the amplitudes in Figs. 5, 6 and 7 and Table 3, the hardness and the residual stress distributions before testing shown in Fig. 1 and 2 were taken into account. The stresses introduced here for discussion are normal stress σ_y in circumferential direction of roller and reversing orthogonal shear stress τ_{yz} which are conventionally applied to rolling contact fatigue, and maximum principal stress σ_1 and maximum shear stress τ_{45° which are applied to fracture of general metallic materials.

In Fig. 5, 6 and 7, the maximum values of the amplitudes $A(\sigma_y/\sqrt{3}Hv)$ and $A(\sigma_1/\sqrt{3}Hv)$ which become maximum on surface are almost

Fig. 7 Distributions of amplitudes $A(\tau/Hv)$ and $A(\sigma/\sqrt{3}Hv)$

the same, and the amplitude $A(\tau_{yz}/Hv)$ and $A(\tau_{45^\circ}/Hv)$ become maximum under the surface, the former being larger than the latter. Since the pitting failure depends upon the normal stress σ_y according to S. Way⁽¹³⁾, the maximum values of the amplitudes $A(\sigma_y/\sqrt{3}Hv)$ and $A(\tau_{yz}/Hv)$ are taken and compared. The maximum value of the amplitude $A(\sigma_y/\sqrt{3}Hv)$ is larger than that of the amplitude $A(\tau_{yz}/Hv)$ in any specimen, and this tendency is remarkable in specimen TA but is not so remarkable in the other specimens as in specimen TA. Therefore it can be considered that in the case of specimen TA only a pitting failure occurred in any condition and in the cases of specimens TA and Q both pitting and spalling failures occurred. About the specimens failed by spalling, the depth where the spalling crack occurred was estimated from Fig. 4 and Table 2 and it agrees well with the depth where the amplitude $A(\tau_{yz}/Hv)$ becomes maximum shown in Table 3.

And in Table 3, the maximum values of the amplitudes $A(\sigma_y/\sqrt{3}Hv)$ and $A(\tau_{yz}/Hv)$ under certain Hertzian stress of specimen TA are the largest followed by specimens TB and Q.

This tendency agrees with the tendency of surface durability.

As above mentioned, it can be said that the pitting due to surface-origin crack depends upon the amplitude $A(\sigma_y/\sqrt{3}Hv)$ and the spalling due to subsurface-origin crack depends upon the amplitude $A(\tau_{yz}/Hv)$, and the surface durability can be explained by these amplitudes. Fig. 8 shows the relationship between the maximum amplitude A_{max} and the number of cycles N obtained from the experimental and analytical results shown in Fig. 3 and Table 3. In Fig. 8, $[A(\sigma_y/\sqrt{3}Hv)]_{max}$ and $[A(\tau_{yz}/Hv)]_{max}$ is plotted on the ordinate in the cases of specimens failed by pitting and spalling respectively, the abscissa being N . The relation between A_{max} and N can be presented by equation $10^{8.5-7 A_{max}} \cdot N = 10^{12.1}$ as average and plotted points are within the band limited by fine solid lines. From the standpoint

Table 3 Values and depths of maximum amplitudes $[A(\sigma/\sqrt{3}Hv)]_{max}$ and $[A(\tau/Hv)]_{max}$

Specimen mark	Pmax kg/mm ²	$A(\sigma_1/\sqrt{3}Hv)$			$A(\sigma_y/\sqrt{3}Hv)$			$A(\tau_{45^\circ}/Hv)$			$A(\tau_{yz}/Hv)$		
		Amax	z mm	Hv	Amax	z mm	Hv	Amax	z mm	Hv	Amax	z mm	Hv
TA	100	0.095	0.00	333	0.093	0.00	333	0.041	0.20	300	0.081	0.15	305
	110	0.105	0.00	333	0.103	0.00	333	0.047	0.20	300	0.090	0.15	305
	120	0.114	0.00	333	0.113	0.00	333	0.052	0.20	300	0.098	0.20	300
	130	0.123	0.00	333	0.122	0.00	333	0.056	0.20	300	0.107	0.20	300
	140	0.133	0.00	333	0.132	0.00	333	0.062	0.30	290	0.116	0.20	300
TB	110	0.062	0.00	560	0.061	0.00	560	0.023	0.15	488	0.057	0.20	471
	120	0.067	0.00	560	0.067	0.00	560	0.026	0.20	471	0.063	0.20	471
	130	0.073	0.00	560	0.072	0.00	560	0.029	0.20	471	0.068	0.20	471
	140	0.079	0.00	560	0.078	0.00	560	0.033	0.25	461	0.074	0.20	471
	150	0.085	0.00	560	0.084	0.00	560	0.036	0.25	461	0.080	0.25	461
Q	130	0.056	0.00	728	0.056	0.00	728	0.027	0.10	719	0.047	0.20	683
	140	0.061	0.00	728	0.060	0.00	728	0.028	0.10	719	0.052	0.30	631
	150	0.065	0.00	728	0.065	0.00	728	0.028	0.10	719	0.057	0.30	631
	160	0.070	0.00	728	0.069	0.00	728	0.030	0.05	726	0.061	0.30	631
	170	0.074	0.00	728	0.073	0.00	728	0.031	0.05	726	0.066	0.35	610

$$\mu = 0.05, \quad \nu = 0.3, \quad E = 21000 \text{ kg/mm}^2$$

of safety design, the fatigue life N or the maximum amplitude $A_{\max}$ can be determined by an equation $10^{85.7 A_{\max}} \cdot N = 10^{11.6}$.

In Fig.8 the tendency about specimen TA is seen to be considerably different from that about the other specimens. Therefore, the hardness distribution of each specimen after the rolling contact fatigue tests was measured, and it was made clear that the soft specimens TA and TB were considerably work-hardened. Consequently, considering the hardness distribution after fatigue tests in calculation of the maximum amplitude $A_{\max}$ about specimens TA and TB, the tendency about specimens TA and TB in Fig.8 agrees almost with that of the equation $10^{85.7 A_{\max}} \cdot N = 10^{12.1}$ as shown in this figure. It can be considered that this fact is due to self-strengthening⁽¹⁴⁾ during the rolling contact fatigue.

3. Evaluation of surface durability by hardness

The results of these supplementary and previous^{(4) (5) (6) (7) (8)} investigations are summarized in Table 4 which shows surface hardness, surface failure mode, Hertzian stress at fatigue life of 10^6 , 10^7 and 5×10^7 cycles, maximum amplitude $A_{\max}$ under each

Hertzian stress, depth of $A_{\max}$ and hardness at this depth for each specimen. As for $[A(\sigma_y/\sqrt{3}Hv)]_{\max}$, $[A(\tau_{yz}/Hv)]_{\max}$ and $[A(\tau_{45^\circ}/Hv)]_{\max}$, in the case of annealed S45C roller A and thermally refined S45C rollers T and TA where the pitting was predominant, the maximum amplitude $[A(\sigma_y/\sqrt{3}Hv)]_{\max}$ was largest, and in the cases of case hardened nickel chromium steel SNC21

Fig.8 $A_{\max}$ - N curves

Table 4 Values and depths of maximum and peak amplitudes $A_{\max}$ and A_{peak} at each fatigue life

Roller material	Specimen mark	Surface hardness	Mating roller	Surface failure mode	N	P _{max} kg/mm ²	(A(σ _y /√3Hv)) _{max}	Z (mm)	Hv	(A(τ _{yz} /Hv)) _{max}	Z (mm)	Hv	(A(τ _{45°} /Hv)) _{peak}	Z (mm)	Hv	(A(σ _y /√3Hv)) _{max}	Hv*
Annealed S45C	A	180	A	Pitting	10 ⁶ 10 ⁷ 5x10 ⁷	115 50	0.198 0.085	0 0	180 180							0.114 0.068	320 225
Thermal-refined S45C	T	300	T	Pitting	10 ⁶ 10 ⁷ 5x10 ⁷	105 80	0.109 0.082	0 0	300 300							0.077 0.063	424 390
	TA	333	C	Pitting	10 ⁶ 10 ⁷ 5x10 ⁷	125 96	0.117 0.089	0 0	333 333							0.080 0.072	485 410
	TB	560	C	Pitting (Spalling)	10 ⁶ 10 ⁷ 5x10 ⁷	139 121 109	0.078 0.067	0 0	560 560	0.074 0.063	0.20 0.20	471 471				0.069 0.061	632 614
Through-hardened S45C	Q	728	C	Spalling (Pitting)	10 ⁶ 10 ⁷ 5x10 ⁷	171 137	0.073 0.058	0 0	728 728	0.067 0.051	0.35 0.30	610 631				0.069 0.056	770 760
Induction-hardened S45C	IA	746	IA C	Spalling (Pitting)	10 ⁶ 10 ⁷ 5x10 ⁷	167 157 151	0.070 0.065 0.063	0 0 0	746 746 746	0.061 0.055 0.052	1.60 1.60 0.20	228 228 712	0.061 0.055 0.050	1.60 1.60 1.60	228 228 228		
	IB	755	IB C	Spalling (Pitting)	10 ⁶ 10 ⁷ 5x10 ⁷	181 169 160	0.075 0.070 0.066	0 0 0	755 755 755	0.063 0.059 0.055	0.25 0.25 0.25	715 715 715	0.044 0.039 0.035	2.80 2.80 2.80	219 219 219		
	IC	754	IC C	Spalling (Pitting)	10 ⁶ 10 ⁷ 5x10 ⁷	183 166 155	0.076 0.069 0.064	0 0 0	754 754 754	0.063 0.057 0.053	0.30 0.25 0.25	708 720 720					
Case-hardened SNC21	CA	800	CA	Spalling	10 ⁶ 10 ⁷ 5x10 ⁷	210 188 172				0.096 0.083 0.073	0.45 0.45 0.45	513 513 513					
	CB	855	CB	Spalling (Pitting)	10 ⁶ 10 ⁷ 5x10 ⁷	228 205 189				0.075 0.063 0.058	0.65 0.40 0.35	640 775 787					
	CC	855	CC	Spalling	10 ⁶ 10 ⁷ 5x10 ⁷	222 199 183				0.071 0.063 0.058	0.30 0.30 0.30	790 790 790					
Nitrided SACM1	NA	1140	NA	Spalling	10 ⁶ 10 ⁷ 5x10 ⁷	96 90				0.059 0.053	0.35 0.35	300 300	0.059 0.053	0.35 0.35	300 300		
	NB	1220	NB	Spalling	10 ⁶ 10 ⁷ 5x10 ⁷	109 100				0.058 0.049	0.50 0.50	294 294	0.058 0.049	0.50 0.50	294 294		
	NC	1150	NC	Spalling	10 ⁶ 10 ⁷ 5x10 ⁷	117 110				0.050 0.044	0.75 0.75	285 285	0.050 0.044	0.75 0.75	285 285		

Hv* : Surface hardness after rolling contact fatigue test

rollers CA, CB and CC and nitride-hardened aluminium chromium molybdenum steel SACM1 rollers NA, NB and NC where the spalling was predominant, the maximum amplitude $[A(\tau_{yz}/Hv)]_{\max}$ was largest in most cases. And in the cases of thermally refined S45C roller TB, through hardened S45C roller Q, induction-hardened S45C rollers IA, IB and IC where the pitting and the spalling occurred, there was little difference between the maximum amplitudes $[A(\sigma_y/\sqrt{3}Hv)]_{\max}$ and $[A(\tau_{yz}/Hv)]_{\max}$. In these last cases both values of the maximum amplitudes $[A(\sigma_y/\sqrt{3}Hv)]_{\max}$ and $[A(\tau_{yz}/Hv)]_{\max}$ are shown in Table 4. The failure of specimens IA, IB, NA, NB and NC was due to the spalling crack which occurred at the vicinity of case-core boundary, or case crashing. Therefore for these specimens the peak amplitude $[A(\tau_{yz}/Hv)]_{\text{peak b}}$ at the case-core boundary was also shown in Table 4. For softer roller specimens, considering the hardnesses Hv^* after rolling contact fatigue tests, the modified maximum amplitude $[A(\sigma_y/\sqrt{3}Hv^*)]_{\max}$ is also shown in this table.

A series of the results shown in Table 4 have been discussed assuming that there is a linear relationship between strength and hardness of materials. In order to confirm this linear relationship, torsional tests were performed by using the specimens with hardness of Hv214 to Hv572 which had been obtained from the same lot of S45C steel as specimens TA, TB, Q, IA, IB and IC by various heat treatments. And the relationship between Vickers hardness Hv and shear strength τ_B was obtained. The results are shown in Fig.9 which is presented using an equation $\tau_B = 0.167 \cdot Hv^{1.07}$. Even if the above mentioned supplementary experimental results were discussed in terms of the amplitudes $A(\sigma/\sqrt{3}\tau_B)$ and $A(\tau/\tau_B)$ using that equation instead of the amplitudes $A(\sigma/\sqrt{3}Hv)$ and $A(\tau/Hv)$ the tendencies in the values and the depths of $A_{\max}$ were hardly influenced. Therefore, it could be confirmed that the surface failure and the surface durability can be reasonably discussed in terms of the amplitudes $A(\sigma/\sqrt{3}Hv)$ and $A(\tau/Hv)$.

When surface durability is discussed in relation to hardness, surface hardness is simply taken as the representative index of surface durability. The relationship

Fig.9 Relationship between Vickers hardness and shear strength

between surface durability and surface hardness after H. Rettig⁽²⁾ is presented as a solid line in Fig.10. The experimental results shown in Table 4 are plotted on the same scale in this figure for comparison. The results of soft specimens on which the pitting occurred agree well with the solid line but the results of surface hardened specimens, especially nitrided specimens on which the spalling occurred agree hardly with this solid line. Where, surface-endurance limits are defined in the case of specimens A, T, TA, TB, Q, NA, NB, and NC by Hertzian stress for 10^7 cycles life since knees of $p_{\max}$ -N curves of these specimens tended to exist at about 10^7 cycles, and in the case of specimens IA, IB, IC, CA, CB, and CC by Hertzian stress for 5×10^7 cycles life since in these cases the knees did not appear at cycles over 10^7 . On the other hand, the relationship between the hardness at the depth of crack initiation and the amplitude $A(\sigma_y/\sqrt{3})$ or $A(\tau_{yz})$ for the surface-endurance limit at this depth is plotted in Fig.10 using the results of Table 4.

According to the results of these supplementary and previous investigation⁽⁵⁾⁽⁸⁾, the crack initiation position was regarded as the position of the maximum amplitude $[A(\sigma_y/\sqrt{3}Hv)]_{\max}$ for pitting and as the depth of the maximum amplitude $[A(\tau_{yz}/Hv)]_{\max}$ or the peak amplitude $[A(\tau_{yz}/Hv)]_{\text{peak b}}$ for spalling. Therefore, as for stress amplitudes $A(\sigma_y/\sqrt{3})$ and $A(\tau_{yz})$ in Fig.10, in the case of pitting the relationship between the amplitude $A(\sigma_y/\sqrt{3})$ and the hardness Hv at the position of maximum amplitude $[A(\sigma_y/\sqrt{3})]_{\max}$ respectively is plotted, and in the case of spalling the relationship

Fig.10 Relationship between surface hardness and surface durability, and relationship between hardness at depth of $A_{\max}$ or $A_{\text{peak b}}$ and amplitude of $A(\sigma_y/\sqrt{3})$ or $A(\tau_{yz})$

between the amplitude $A(\tau_{yz})$ and the hardness H_v at the depth of maximum amplitude $[A(\tau_{yz}/H_v)]_{\max}$ or the peak amplitude $[A(\tau_{yz}/H_v)]_{\text{peak } b}$ respectively where the spall initiated is plotted. And in the case where pitting and spalling failures occurred, both relationships are plotted.

In the case of soft specimens, that relationship is plotted concerning the maximum amplitude $[A(\sigma_y/\sqrt{3}H_v)]_{\max}$ instead of $[A(\sigma_y/\sqrt{3}H_v)]_{\text{peak } b}$. The maximum amplitude $[A(\sigma_y/\sqrt{3}H_v)]_{\max}$, $[A(\sigma_y/\sqrt{3}H_v)]_{\text{peak } b}$, $[A(\tau_{yz}/H_v)]_{\max}$ or the peak amplitude $[A(\tau_{yz}/H_v)]_{\text{peak } b}$ gives a characteristic value for the initiation of failure, and the relationship between the hardness H_v and the amplitude $A(\sigma_y/\sqrt{3})$ or $A(\tau_{yz})$ at the position of the maximum amplitude $A_{\max}$ or the peak amplitude $A_{\text{peak } b}$ respectively is represented well by an equation $A(\sigma_y/\sqrt{3}), A(\tau_{yz}) = 0.041 \cdot H_v^{1.06}$.

This relationship is similar to that shown in Fig. 9 and a proportional equation

$A(\sigma_y/\sqrt{3}), A(\tau_{yz}), \tau_B \propto H_v^{(1.06-1.07)}$ is introduced while an equation

$A(\sigma_y/\sqrt{3}), A(\tau_{yz}) \approx 0.25\tau_B$ is introduced independently of hardness.

As above mentioned, the surface durability of soft specimens on which the pitting due to surface-origin crack occurred can be reasonably and simply explained by surface hardness. Namely, in the cases of soft specimens A, T, TA and TB, the relation $p_{\max} = (0.2-0.3) H_v$ is introduced from Table 4 between surface Brinell hardness H_b and surface durability $p_{\max}$. This relationship agrees with that after E. Buckingham⁽¹⁴⁾⁽¹⁵⁾. However, the surface durability of nitrided specimens, whose surface hardnesses are very high comparing with other specimens, is comparatively low as shown in Table 4 and Fig. 10. The failure mechanism of spalling whose crack initiates under the surface is different from that of pitting which has origin on the surface. Therefore, it is not so significant to relate surface durability with surface hardness. In order to clarify the relationship between surface durability and hardness considering surface failure mechanism, it would be reasonable to take the correlation between the initiation depth of failure and the depth of the maximum or peak amplitude $A_{\max}$ or $A_{\text{peak } b}$ and the relation between the value of $A_{\max}$ or $A_{\text{peak } b}$ are discussed. According to the above mentioned consideration, the relationship between the value of $A_{\max}$ or $A_{\text{peak } b}$ and the hardness at the depth of $A_{\max}$ or $A_{\text{peak } b}$ is shown in Fig. 11 from the results of Table 4 taking fatigue life N as a parameter. In Fig. 11, the results about pitting and spalling failure are shown as in the case of Fig. 10. Sub-letters of alphabet in Fig. 11 indicate that the maximum amplitude $[A(\sigma_y/\sqrt{3}H_v)]_{\max}$ is modified to $[A(\sigma_y/\sqrt{3}H_v^*)]_{\max}$ considering the work-hardening of soft specimens. In Fig. 11, when the hardness at the depth of $A_{\max}$ is more than H_v550 , the value of $A_{\max}$ is in the range of 0.063 to 0.076 for the fatigue life of 10^6 cycles and is 0.051 to 0.063 for the fatigue life of 10^7 to 5×10^7 cycles independently of hardness. When the hardness is less than H_v550 , the value of $A_{\max}$ tends to increase as the hardness decreases.

The relationship between the peak amplitude $A_{\text{peak } b}$ and the hardness in the case of the spalling due to the crack initiation at the vicinity of case-core boundary is different from the tendency of the relationship between the maximum amplitude $A_{\max}$ and the hardness. The value of $A_{\text{peak } b}$ is in the range of 0.035 to 0.055 for the fatigue life of 10^7 to 5×10^7 cycles and when $A_{\text{peak } b}$ is compared with $A_{\max}$ at the same fatigue life, it is less than the value of $A_{\max}$. This fact may be due to the microstructural changes in both hardness and residual stress at the vicinity of case-core boundary.

From the above discussion, the surface durability can be conservatively determined by an equation $A_{\max} = 0.051$ and by an equation $A_{\text{peak } b} = 0.035$ for case-core boundary from the standpoint of design when the surface durability is defined by Hertzian stress for the fatigue life of 10^7 to 5×10^7 cycles. Namely, when the hardness and residual stress distributions of machine elements used under contact stress are known, the allowable Hertzian stress can be calculated by using their critical values. And if the hardness and residual stress distributions can be controlled by heat treatments, optimum design for surface durability can be made by those critical equations.

4. Conclusions

In order to clarify the surface durability and the surface failure concerning hardness, various heat-treated rollers were tested and the results were discussed. The summarized results are as follows:

(1) The surface failure modes were pitting on annealed and thermally refined S45C specimens with surface hardness of H_v180 to H_v333 , pitting and spalling on thermally refined, through hardened and induction-hardened S45C specimens with H_v560 to H_v755 and spalling on case-hardened SNC21 and nitrided SACM1 specimens with H_v800 to H_v1220 . It can be said that pitting and spalling failures depend upon the normal stress σ_y in circumferential direction of roller and the orthogonal shear stress τ_{yz} respectively, and the surface failure mode can be approximately estimated by the exa-

Fig. 11 Relationship between value of $A_{\max}$ or $A_{\text{peak } b}$ and hardness at depth of $A_{\max}$ or $A_{\text{peak } b}$

mination of the amplitudes $[A(\sigma_y/\sqrt{3}Hv)]_{\max}$, $[A(\tau_{yz}/Hv)]_{\max}$ and $[A(\tau_{yz}/Hv)]_{\text{peak } b}$.

(2) The surface durability must be discussed not simply in terms of surface hardness but in terms of the amplitude $A_{\max}$ or $A_{\text{peak } b}$ and the hardness at the depth of $A_{\max}$ or $A_{\text{peak } b}$ considering the surface failure mechanism which is influenced by the hardness, hardened depth, hardness distribution, etc. From the standpoint of machine element design, when the hardness and residual stress distributions are known, the surface durability can be calculated by using equations $A_{\max} = 0.051$ and $A_{\text{peak } b} = 0.035$.

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