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Estimation of Fatigue Strength Enhancement for Carburized and Shot-Peened Gears

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An experimental formula has been proposed to estimate the bending fatigue strength of carburized gears from the hardness and the residual stress. The derivation of the formula is briefly reviewed, and the effectiveness of the formula is demonstrated in this article. The comparison with many test results for carburized and shot-peened gears verifies that the formula is effective for the approximate estimation of the fatigue strength. The formula quantitatively shows a way of enhancing fatigue strength, i.e., the increase of hardness and residual stress at the fillet. The strength is enhanced about 300 MPa by an appropriate shot peening, and it can be improved still more by the surface removal by electropolishing.

Introduction

THE use of a gear system, which reduces turbine speed and rotates the fan, enables the flexible design of the air breathing propulsion engine. For this purpose, some problems should be solved. The dynamic analysis of the gear system is one of them. Buyukataman[1] surveyed the previous studies of gear system dynamics and discussed the design criteria and analysis of epicyclic gears for aircraft.

The increase of the load carrying capacity of gears is another important problem for a reliable design and the reduction of weight. The American Gear Manufacturers Association (AGMA) standard[2] prescribes for the materials, heat-treatment, etc., of the aircraft gears. The standard recommends AISI 9310 for gear material and a carburization for its normal treatment. The high-load capacity of carburized gears mainly originates from the existence of hardened layer and compressive residual stress. Seabrook and Dudley[3] summarized the bending strength of carburized AISI 9310 gears. Townsend et al.[4] performed a high-speed running test of the gear to clear the load capacity and the effect of lubrication. Yuruzume and Mizutani[5] reported a result of bending fatigue test for high-speed gears. However, the effects of both hardened layer and residual stress on the bending strength were not made clear in these researches.

On the other hand, Aida et al.,[6] Rettig,[7] Nishioka et al.,[8] and Tobe and Maruyama[9] obtained the fatigue strength of general-purpose carburized gears, and discussed the effect of the residual stress on the strength. The authors have also performed the fatigue tests,[10–12] and proposed an experimental formula for the estimation of the fatigue strength.

In this article, the point of the tests and the derivation of the experimental formula are reviewed first. Then the formula is applied to many test results including the results for AISI 9310 carburized gears, and the effectiveness of the formula is discussed and verified. In this verification, the residual stress which is not presented in the reports is evaluated by the method proposed by the authors.[13] Based on the formula, the enhancement of strength due to shot peening and electropolishing is also demonstrated.

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Bending Fatigue Test Procedure

Test Gears

The dimensions of test gears which were mainly used in the authors' fatigue tests are shown in Table 1. The gear blanks are made of the low alloy steels SCM415 and SCM420H. The chemical compositions of these materials are indicated in Table 2, and they are practically identical except for the carbon content. In this table the chemical compositions of other materials, which will be referred to later, are also tabulated. The machining and heat-treatment process is presented in Fig. 1. The blanks are copper-plated about 20 μm thick to prevent the gear sides from carburizing, and this makes the longitudinal characteristics of test gears approximately uniform. Then the gears are hobbed. The cutter, as shown in Table 3, is for one of the standard basic rack tooth profiles in the Japanese Industrial Standards (JIS)[14] as well as the International Organization for Standardization (ISO).[15]

The test gears are finally gas carburized. The carburizing temperature T_1 and time t_1, the diffusing time t_2 and the tempering temperature T_2 are listed in Table 4. The AGMA standard[16] recommends the case depth. Referring to this, the effective case depth d_{eff} (depth to 550 Hv) of gears Nos. 1–3 and No. 8 are decided to be 0.9 mm. To clear the effects of case depth and residual stress on the strength, gears Nos. 4–7 are also prepared. Gears in No. 6 are not carburized but heat-treated in the same way as the gears in No. 2.

Some teeth are carefully cut off along the normal to the tooth fillet at the critical section, and the hardness distribution along the depth is measured on the cut and polished surface. The surface hardness H_s is about 50 Hv lower than the maximum hardness H_{max} at 0.2–0.3 mm below the surface. The core hardness H_c is 310–360 Hv. The measured effective case depth and hardness are summarized in Table 4.

The surface residual stress σ_R of all test teeth and the amount of retained austenite γ are measured by X-ray diffraction method. The details of measurement are presented in a previous report.[10] The residual stress of the test gears in Table 4 is not very high.

Table 1 Dimensions of test gears

Module m, mm	5
Number of teeth z	18
Profile modification coefficient x	0
Face width b, mm	8.0 ± 0.01
Tip diameter, mm	100.0 ± 0.01
Finish	Hobbed
Heat-treatment	Carburized
Gear grade	JIS 4

Table 2 Chemical compositions of test gear materials [wt %] (measured except AISI 9310)

	C	Si	Mn	P	S	Cr	Mo	Ni
SCM415	0.15	0.31	0.77	0.020	0.022	1.04	0.18	——
SCM415[a]	0.15	0.18	0.73	0.02	0.03	1.03	0.19	——
SCM418	0.20	0.19	0.77	0.010	0.026	1.18	0.17	0.05
SCM420H	0.20	0.28	0.79	0.022	0.011	0.17	0.14	——
SNCM420	0.18	0.27	0.47	0.007	0.015	0.57	0.18	1.75
SNCM616	0.15	0.31	0.90	0.019	0.022	1.58	0.54	2.95
SNC815	0.14	0.23	0.52	0.013	0.017	0.84	——	3.07
MAC14[b]	0.16	0.29	0.51	0.024	0.020	2.51	0.36	0.10
AISI9310	0.07–0.14	0.20–0.35	0.40–0.70	<0.040	<0.040	1.00–1.45	0.08–0.15	2.95–3.55

[a]Material for Nos. 22–25. [b]Standard name of Mitsubishi Steel Manufacturing Co., Ltd.

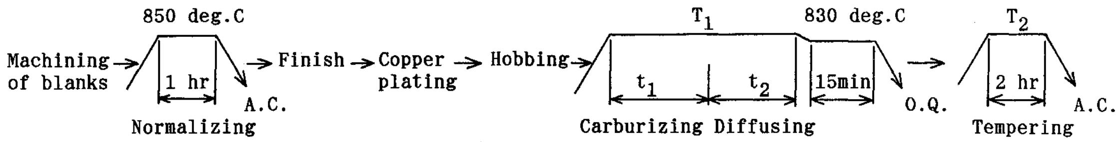

Fig. 1 Machining and heat-treatment process of gears Nos. 1–8.

Fatigue Test Procedure

Two electrohydraulic servocontrolled fatigue testers are used in the authors' test. The loading device and its control are illustrated in Fig. 2. The load is well controlled and the fluctuation is less than 1%. The sine-wave pulsating load is applied at the position of 0.5 mm below the tip with a speed of 30–50 Hz. The stress ratio is about 0.008.

The authors are of the opinion that the gear strength should be expressed by the true stress, and have calculated the fillet stress of the gears, which are generated by the basic rack shown in Table 3, by two-dimensional FEM.[17] The maximum tensile stress σ_t[MPa] due to normal load P_n[N] is expressed as follows:

$$\sigma_t = \frac{P_n}{bm}\left[a_1\left(\frac{1}{z}\right) + a_2\left(\frac{1}{z}\right)^3 + 3.50\right] \times \exp\left\{\left[2.50\left(\frac{1}{z}\right) - 0.50\right]\frac{\lambda}{m}\right\} \quad (1)$$

$$a_1 = 2.50 - 18.00x$$

$$a_2 = 2600\exp(-2.75x) \quad (x < 0.40)$$

$$a_2 = 2600\exp(-2.75 \times 0.40) \quad (x \geq 0.40)$$

where m[mm]: module, b[mm]: face width, z: number of teeth, x: addendum modification coefficient, λ[mm]: distance from the tip [radius of tip circle $= zm/2 + (1 + x)m$] to the loading point along the centerline of tooth. This formula is applicable to any gear teeth of $z = 18$ to rack, and $x = -0.4$ to 0.6 without undercut. The stress level S in the fatigue test is represented by the stress obtained from Eq. (1).

The ISO strength rating formula[18] recommends the life factor of unity at the life $N \geq 3 \times 10^6$ for heat-treated gears. Referring to this, the test is terminated at $N = 3 \times 10^6$, and it is considered as nonfailure. The staircase method[19] is adopted to estimate the fatigue strength.

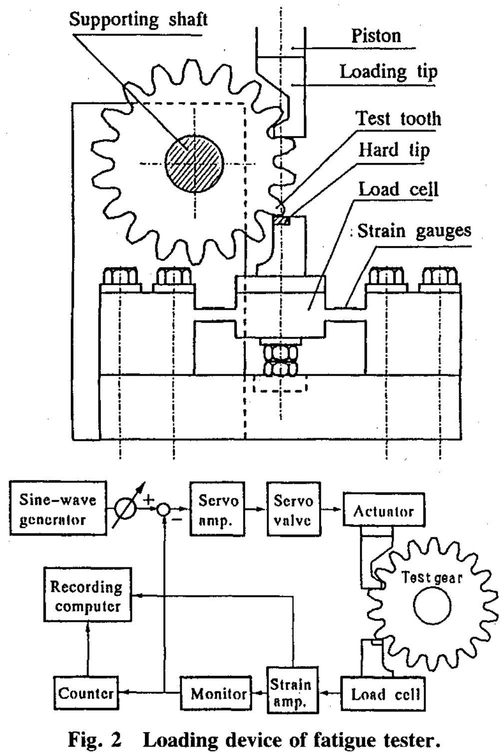

Fig. 2 Loading device of fatigue tester.

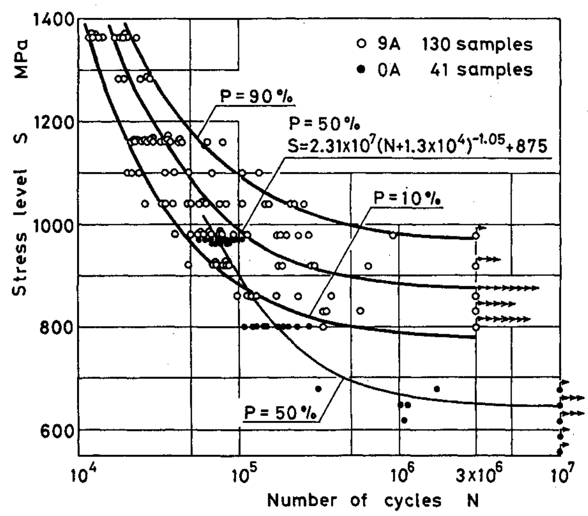

Fig. 3 Fatigue lives of gears No. 1 and No. 6 and estimated PSN curves.

Formula for the Estimation of Fatigue Strength

Fatigue Test Results

The test results for gears No. 1 and No. 6 are shown in Fig. 3. For No. 1, 130 samples were tested in 10 stress levels. The mean SN curve and two SN curves of probability of rupture $P = 10$ and 90% are obtained as illustrated in the figure. The distributions of both fatigue strength and life were examined, and it was found that they could be considered as the normal distribution and the log-normal distribution,[10] respectively.

Mean SN curves for all test gears in Table 4 are shown in Fig. 4. The gears with the case depth recommended in the AGMA standard have slightly higher strength, however, the effect of case depth on the bending strength is not very remarkable. The obtained fatigue strength σ_u are listed in Table 4. The residual stress as well as the amount of retained austenite remained approximately constant during the fatigue test.

Derivation of the Experimental Formula

The fatigue strength σ_u[MPa] is assumed to be expressed as the function of core hardness H_c[Hv], surface hardness H_s[Hv] and surface residual stress σ_R[MPa]

$$\begin{aligned}\sigma_u &= \sigma_{uc} + \sigma_{usc} + \sigma_{uR} \\ &= f(H_c) + g(H_s - H_c) + h(\sigma_R) \qquad (2)\end{aligned}$$

where, σ_{uc}[MPa] shows the fatigue strength of noncarburized gears, σ_{usc}[MPa], and σ_{uR}[MPa] indicate the increase of strength due to hardened layer and residual stress, respectively.

The test gears in No. 1 are divided into four groups A–D based on the residual stress. The fatigue strengths of every group are plotted in Fig. 5. The number of samples is shown in the figure. Other characteristics are assumed to be the same, and the contribution of residual stress to the increase of fatigue strength is derived as follows:

$$\sigma_{uR} = -0.5\sigma_R \qquad (3)$$

The contribution of residual stress of the gears in No. 6 is evaluated by this equation, and it is subtracted from the obtained strength. The result is plotted against the core hardness in Fig. 6. The core hardness is used here because of the small difference between the core hardness and the surface hardness. The strength of gears in No. 7 and normalized steel gears[20] are also plotted in the figure. The effect of core hardness is, therefore, obtained by the following expression:

$$\sigma_{uc} = 1.17H_c + 257 \qquad (4)$$

Figure 7 illustrates the effect of hardened layer, which is obtained by subtracting σ_{uR} and σ_{uc} from the fatigue strength of carburized gears. Some plots obtained from the fatigue strength of shot-peened gears, which will be discussed later, are included in the figure. The effect is given by

$$\sigma_{usc} = 3.1 \exp[0.0097(H_s - H_c)] \qquad (5)$$

Accordingly, the fatigue strength is represented by the following expression:

$$\sigma_u = 1.17H_c + 257 + 3.1 \exp[0.0097(H_s - H_c)] - 0.5\sigma_R \qquad (6)$$

The fatigue strengths estimated by Eq. (6) are compared with the experimental results in Fig. 8. The plots are numbered to specify the test gears listed in Table 4. The error of estimation is about 4% at most, and the fatigue strength of gears Nos. 1–8 can be estimated well by the formula.

Table 3 Cutter dimensions

Pressure angle, deg	20
Top clearance	$0.25m$
Radius of tip corner	$0.375m$

Verification of the Experimental Formula

Comparison with Fatigue Test Results for Carburized Gears

To verify the effectiveness of the experimental formula, the fatigue test results for carburized gears, of which hardness and residual stress are measured, are indispensable. However, few reports including such measurement have been presented. The suitable reports are surveyed and the test results are listed in Table 5.

Number 9[11] and Nos. 14–16[12] were the results obtained by the authors. In the former test, the test gears were carburized by a process similar to No. 8, but ammonia gas of 1 l/min was added in 15 min at the last carburizing stage. The latter test was conducted to make clear the size effect of fine module gears. Since the tooth was too small to apply the ordinary X-ray stress measurement method, only a few residual stresses were measured especially by using a narrow X-ray beam. Numbers 10–12[21] were performed in the authors' laboratory. Number 13[9] was the first experimental work for carburized gears in the authors' laboratory. The residual stress was measured for only a few gears.

In Nos. 17–21,[8] rather large teeth were tested. The fillet stress was measured by using strain gauges, and it was used as the stress level. The residual stress was obtained by the dissection method and X-ray method. The residual stresses of the gears Nos. 22–25[6] were measured by a kind of dissection method, and they were comparatively high. The gears in No. 26[22] were supercarburized. The carbon content at the tooth surface was about 2–4%, and the treatment was characterized by the carbide precipitation and martensite in the case.

Numbers 27–37[3] are the test results for AISI 9310 carburized gears. The strengths were originally presented in terms

Table 4 Fatigue test results for carburized gears (1)

No.	Code	m, mm	z	b, mm	Material	T_1 deg C	T_2 deg C	t_1, h/min	t_2, min	d_{eff}, mm	H_s, Hv	H_{max}, Hv	H_c, Hv	γ, %	σ_R, MPa	σ_u, MPa
1	9A	5	18	8	SCM420H	930	170	3:40	20	0.89	680	740	360	22	−240	875
										0.06	33	15	13	3	80	74
2	9B	"	"	"	"	930	170	3:40	20	0.90	695	740	355	22	−100	800
										0.04	24	6	14	3	30	——
3	9C	"	"	"	"	930	150	3:40	20	0.90	710	750	345	25	−130	800
										0.03	13	10	6	3	40	——
4	6A	"	"	"	"	900	170	2:20	20	0.60	660	720	350	22	−150	825
										0.03	33	17	9	3	30	——
5	13A	"	"	"	"	930	170	8:00	30	1.27	670	730	350	25	−160	785
										0.05	15	8	13	4	40	——
6	0A	"	"	"	"	Without carburizing others are same as 9B				——	325	325	300	9	−80	650
											41	41	6	——	20	——
7	0B	"	"	"	"	Normalizing				——	195	195	195	0	0	465
											4	4	4	——	——	——
8	C	"	"	"	SCM415	930	170	4:00	0	0.90	745	780	310	22	−250	950
										——	——	——	——	——	——	——

Upper: mean values, lower: standard deviations. Symbol —— means the value is not evaluated or presented. See Ref. 10 for Nos. 1–7, Ref. 11 for No. 8.

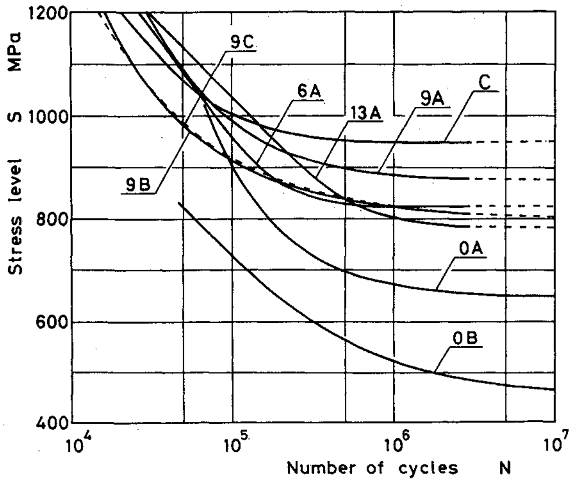

Fig. 4 Estimated mean SN curves of gears in Table 4.

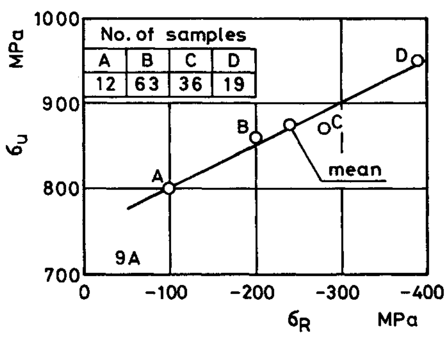

Fig. 5 Effect of residual stress on fatigue strength.

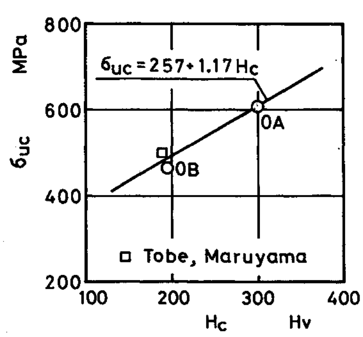

Fig. 6 Effect of core hardness on fatigue strength.

of unit load. Therefore, it is converted into the fillet stress by using Eq. (1), and it is listed as the fatigue strength in the table. If the gears are cut by a basic rack recommended in the AGMA standard (top clearance 0.35 m, radius of tip corner 0.35 m), the fillet stress is about 4% larger[17] than the listed stress. The residual stress is not presented in their report, but it is necessary for the estimation. Therefore, the residual stress is approximately evaluated.[13] In the evaluation, the amount of retained austenite is assumed to be 20%, which is the permissible upper limit for typical aircraft gears.[2] The gears in Nos. 38 and 39[3] are not carburized, but they are listed for the wide verification for 9310 gears. The fatigue strength of these gears is 10% failure strength.

Numbers 40 and 41 are the latest results in the authors' laboratory to clear the effect of heat-treatment on the fatigue strength. The carburizing condition is identical, but the gears in No. 41 are reheated and quenched after normal carburization. This makes the structure metallographically finer than No. 40. However, the gears are slightly shot-blasted after heat treatment. The intensity of blasting is not exactly measured

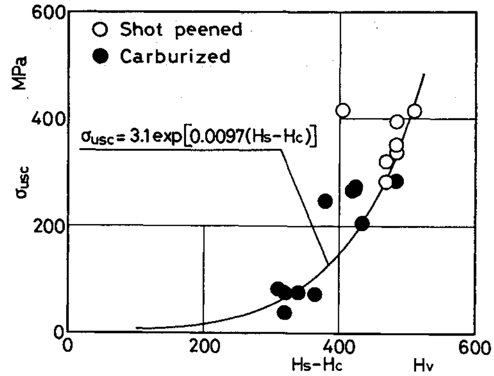

Fig. 7 Effect of hardened layer on fatigue strength.

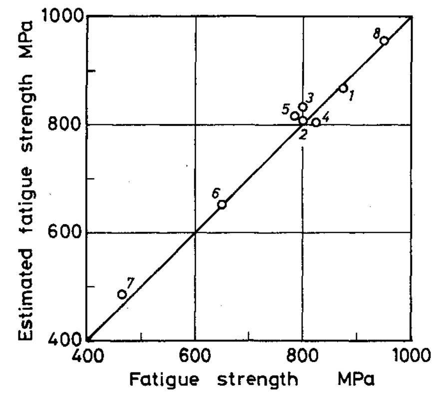

Fig. 8 Comparison of estimated fatigue strength with experimental results (gears in Table 4).

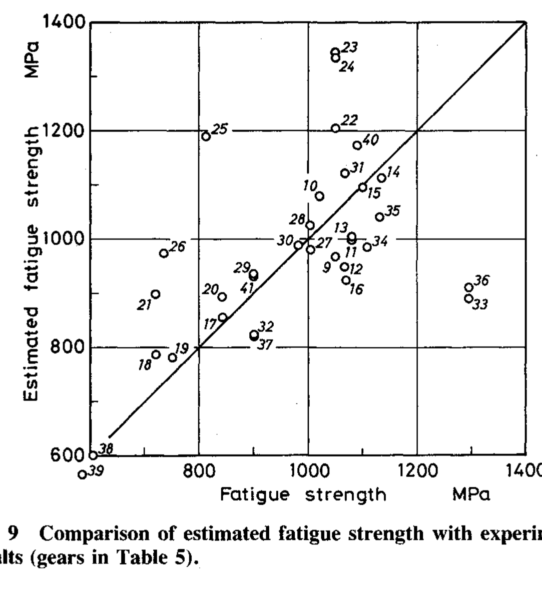

Fig. 9 Comparison of estimated fatigue strength with experimental results (gears in Table 5).

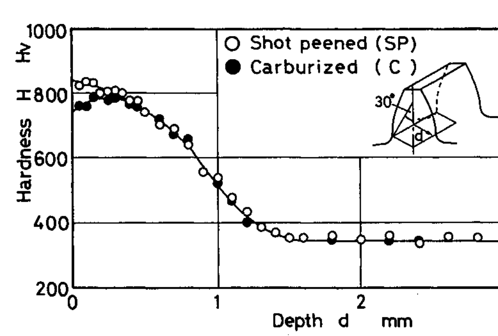

Fig. 10 Increase in hardness due to shot peening.

Table 5 Fatigue test results for carburized gears (2)

No.	Code	m, mm	z	b, mm	Material	T_1 deg C	T_2 deg C	t_1, h/min	t_2, min	d_{eff}, mm	H_s, Hv	H_{max}, Hv	H_c, Hv	γ, %	σ_R, MPa	σ_u, MPa
9	CN	5	18	8	SCM415	930	170	4:00	0	0.93	760	810	340	12	−260	1050
10	Y4	5	18	16	do.	920	200	——	——	0.44	810	810	325	25	−200	1020
										——	——	——	——	——	30	——
11	Y6	〃	〃	〃	〃	920	200	——	——	0.62	755	820	330	17	−330	1080
										——	——	——	——	——	85	——
12	Y8	〃	〃	〃	〃	920	200	——	——	0.85	720	810	340	16	−340	1070
										——	——	——	——	——	60	——
13	M3	3	27	5.15	SCM418	920	200	1:30	120	0.62	750	750	325	——	−350	1080
										——	——	——	——	——	——	62
14	M1.0A	1	98	6	SCM415	850	160	1:30	0	0.27	760	760	330	——	−535	1135
15	M1.25A	1.25	78	6	〃	850	170	1:30	0	0.30	750	750	340	——	−550	1100
16	M1.5A	1.5	64	6	〃	850	170	2:00	0	0.30	740	740	350	——	−240	1070
17	9	8	34	100	SNCM420	930	200	17:00	——	0.80	640	640	240	——	−334	843
18	10	〃	〃	〃	〃	900	200	38:00	——	0.75	600	600	240	——	−294	719
19	11	〃	〃	〃	〃	900	200	82:00	——	1.14	600	600	240	——	−284	749
20	12	〃	〃	〃	SNCM616	930	150	19:00	——	——	650	650	320	——	−372	843
21	13	〃	〃	〃	〃	920	150	76:00	——	——	600	600	400	——	−304	719
22	B	4	18	10	SCM415	930	180	0:30	——	0.30	750	750	280	——	−656	1049
23	C	〃	〃	〃	〃	930	180	1:30	——	0.68	800	800	300	——	−684	1049
24	D	〃	〃	〃	〃	930	180	3:45	——	0.91	800	800	300	——	−664	1049
25	E	〃	〃	〃	MAC14	930	180	9:00	——	1.52	750	750	245	——	−457	813
26	S2	4	29	10	AISI9310	930	170	5:30	——	0.70	730	755	420	——	(−326)	735
27	1	2.54	20	15.9		——	135	——	——	0.56	730	——	377	——	(−373)	1003
28	2	〃	〃	〃	〃					0.51	741	——	399	——	(−428)	1003
29	3	〃	〃	〃	〃					0.51	717	——	356	——	(−317)	899
30	4	〃	〃	〃	〃					0.46	730	——	399	——	(−373)	982
31	5	〃	〃	〃	〃					0.48	765	——	399	——	(−576)	1066
32	6	〃	〃	〃	〃	——	163	——	——	0.89	672	——	337	——	(−181)	899
33	17	〃	〃	〃	〃	——	——	——	——	0.69	694	——	388	——	(−239)	1296
34	19	〃	〃	〃	〃			〃		0.51	730	——	388	——	(−373)	1108
35	21	〃	〃	〃	〃			〃		0.46	717	——	515	——	(−317)	1129
36	23	〃	〃	〃	9310			〃		0.56	705	——	377	——	(−274)	1296
37	29	〃	〃	〃	〃	——	163	——	——	0.64	672	——	337	——	(−181)	899
38	34	〃	〃	〃	〃		Furnace harden			——	293	——	293	——	(0)	606
39	35	〃	〃	〃	〃			〃		——	263	——	263	——	(0)	585
40	DQ	5	18	8	SNC815	930	200	5:00	150	0.94	555	660	420	——	−830	1090
										0.06	7	9	3	——	80	——
41	RQ	〃	〃	〃	〃			〃		1.11	580	750	425	——	−330	900
							Reheat quenching			0.02	6	8	2	——	40	——

Gears in No. 9: ammonia gas of 1 l/min was added in 15 min at the last carburizing stage. Gears in No. 13: $x = -0.573$. Fatigue strength of Nos. 27–39 were originally presented in terms of unit load. Above strengths were estimated by using Eq. (1). The strength of Nos. 38 and 39 are 10% failure strength. Gears in No. 41 were reheat-quenched after normal carburizing and quenching. Gears in Nos. 40 and 41 were shot-blasted after carburization. Residual stress in ( ) were estimated from the hardness. See Ref. 13. See Ref. 11 for No. 9, Ref. 9 for No. 13, Ref. 12 for Nos. 14–16, Ref. 8 for Nos. 17–21, Ref. 6 for Nos. 22–25, Ref. 22 for No. 26, and Ref. 3 for Nos. 27–39.

by using an Almen strip, but it is estimated to be 0.2 mm arc height at highest from the blasting condition.

The estimated fatigue strengths are compared with the experimental results in Fig. 9. The errors of estimation for Nos. 21, 23–25, 26, 33, and 36 are rather large. The authors cannot clear the reason perfectly, but the following may be related to it. The residual stress and surface hardness of Nos. 23 and 24, if anything, are high, and it leads to a higher estimation than the obtained strength. The strength of supercarburized gears No. 26 is lower than was expected, and the carbide precipitation might affect the strength. Seabrook and Dudley[3] described that the 50% failure fatigue strength of carburized 9310 gears was about 55,000 psi unit load. This is approximately equivalent to 1150 MPa, therefore, the fatigue strength of Nos. 33 and 36 might be higher than normal. Except for these results, the average and the maximum error of estimation are about 6.5 and 15%, respectively. It should be noted that the test results for the gears of m = 1–8 mm, z = 18–98, and b = 5–100 mm are examined in this comparison. Accordingly, the authors venture to conclude that the formula can be used for the approximate estimation of the fatigue strength of carburized gear.

Comparison with Fatigue Test Results for Shot-Peened Gears

In this section, the formula is verified based on the results for shot-peened gears. The usable fatigue test results are summarized in Table 6. All tests were performed by the authors. Townsend and Zaretsky,[23] Lawerenz,[24] and Hisamatsu and Kanazawa[25] have studied the effects of shot peening on surface durability and bending strength, but no usable results are reported. Some test results are presented in the paper by Seabrook and Dudley,[3] however, the residual stresses are not shown. Since the residual stress of carburized and shot-peened gears has not been evaluated successfully, their results are not listed in the table.

The code of gears as carburized and the shot-peening conditions are shown in Table 6. The surface hardness increases 30–80 Hv by shot peening as shown in Fig. 10. The residual stress also increases. An example is illustrated in Fig. 11. Two measurements for shot-peened gears are plotted in the figure. One is obtained by increasing the angle ψ in the X-ray side inclination method in the same direction of shot stream (ψ: same). The other is obtained by increasing ψ in the opposite direction (ψ: opp.).[11] The difference between these values may be owed to the anisotropic texture generated by shot peening, and it decreases at 30 μm below the surface. Fatigue lives and SN curves are shown in Fig. 12. The fatigue strength is improved about 280 MPa by shot peening.

The estimated fatigue strengths are compared with the strength obtained by the experiment in Fig. 13. Except for No. 42, the estimation by Eq. (6) is close to the experimental results, and the maximum error of estimation is about 10%.

Table 6 Fatigue test results for shot-peened gears and electropolished gears

No.	Code	Picked from	Arc height (Type A) mm	Coverage, %	Electropolish, μm	H_s, Hv	H_{max}, Hv	H_c, Hv	γ, %	σ_R, MPa	σ_w, MPa
42	SP1	13A	0.30	3 × 98	0	770	770	365	——	−320	1260
43	SP2	13A	0.56	"	0	860	860	375	——	−280	1170
44	SP3	13A	0.70	"	0	835	835	365	——	−295	1150
45	SP4	9A	0.56	"	0	860	860	380	——	−310	1250
46	SP	C	0.55	"	0	825	825	315	0	−380	1230
47	NP1	CN	0.25	1.5 × 98	0	780	780	330	0	−310	1100
48	NP2	CN	0.55	"	0	790	790	340	0	−270	1020
49	NP3	CN	0.70	"	0	820	820	330	0	−285	1040
50	NP4	CN	0.28	3 × 98	0	740	740	340	0	−315	1030
51	NP5	CN	0.57	"	0	780	780	350	0	−280	1040
52	NP6	CN	0.72	"	0	840	840	340	0	−280	1080
53	NP7	CN	0.29	4.5 × 98	0	790	790	340	0	−290	1080
54	NP8	CN	0.59	"	0	830	830	350	0	−280	1030
55	NP9	CN	0.85	6 × 98	0	810	810	350	0	−270	1050
56	EP1	SP2	0.56	3 × 98	30	860	860	375	——	−670	1400
57	EP2	SP3	0.70	"	30	835	835	365	——	−670	1300
58	DQEP	DQ	(0.20)	——	20	560	670	420	——	−1190	1275
59	RQEP	RQ	(0.20)	——	20	585	755	425	——	−600	1100

Shot size: SAE S-230, hardness: HRC57. Coverage 3 × 98% means 3 times of the full coverage confirmed by the Almen strip. Gears in No. 46 were picked from No. 8. Gears in Nos. 56 and 57 were electropolished after shot peening. Gears in Nos. 58 and 59 were electropolished after shot blasting. Their arc heights are estimated value. See Ref. 11 for Nos. 42–57.

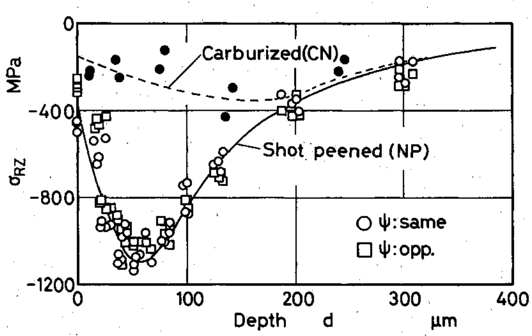

Fig. 11 Increase in residual stress due to shot peening.

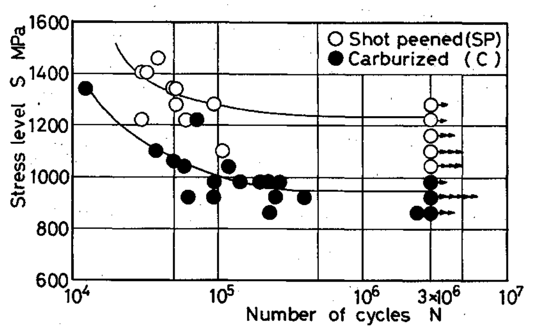

Fig. 12 Fatigue lives of gears No. 8 and No. 46 and estimated SN curves.

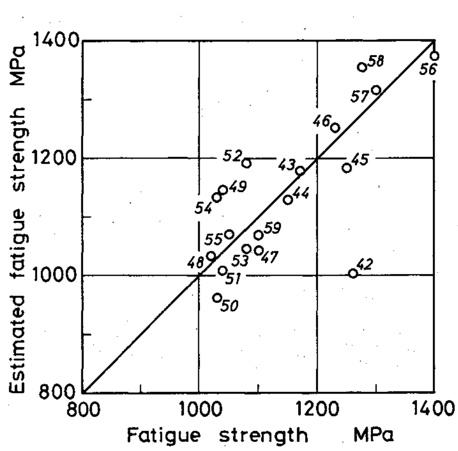

Fig. 13 Comparison of estimated fatigue strength with experimental results (gears in Table 6).

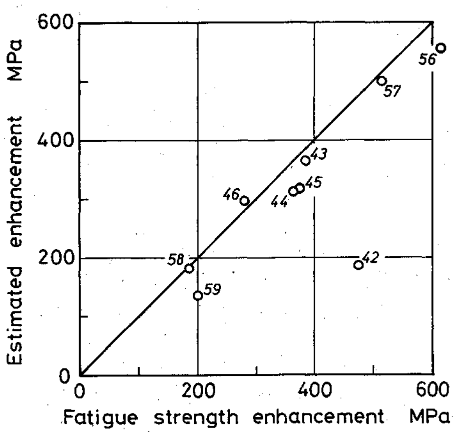

Fig. 14 Comparison of estimated strength enhancement with experimental results.

The gears in Nos. 56–59 are 30–20 μm electropolished after shot peening or shot blasting, and the higher compressive residual stress is exposed at the surface. Even if the metallographic change arises at the surface by electropolishing, it is left out of consideration, and the only changes of residual stress and hardness are taken into account in the estimation. The fatigue strength of electropolished gears can be estimated well by the formula (6).

Enhancement of Fatigue Strength

The formula clearly shows the way of enhancing the strength. The enhancement of fatigue strength owing to shot peening and electropolishing is summarized in Fig. 14. Since there is little improvement of strength in gears Nos. 47–55, they are eliminated. Application of ammonia gas to the gears in No. 9 reduces the retained austenite at the surface. This may affect the strength of gears Nos. 47–55, but it remains unsolved why the strength is not greatly improved by shot peening. From the comparison, it is concluded that the enhancement of strength can be estimated from the formula.

The strength enhancement is plotted against the arc height in Fig. 15. This is obtained from the measured increase in hardness and residual stress. The gears treated with the same carburization are connected by the line. The enhancement of strength reaches the maximum at the arc height of 0.5–0.6 mm in Almen strip A, and it is about 300 MPa. Seabrook and Dudley[3] suggested the 50% failure strength was improved 5000 psi unit loads due to shot peening, however, it is ap-

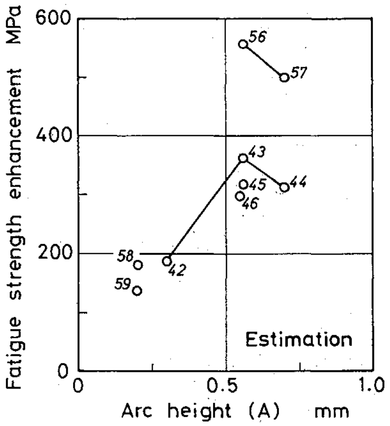

Fig. 15 Estimated strength enhancement due to shot peening and electropolishing.

proximately one-third of the above mentioned enhancement. Figure 15 also demonstrates that electropolishing enhances the strength still more after shot peening. This is mainly caused by the high residual stress exposed at the surface. The enhancement of gears Nos. 56 and 57 is about 200 MPa. In the case of Nos. 58 and 59, which are slightly shot blasted and electropolished, the strength is improved about 150 MPa.

Conclusions

The load-carrying capacity is one of the most significant factors for the reliable design of gear systems used in the air breathing propulsion engine. From this point of view, the bending fatigue tests for carburized gears and the derivation of experimental formula for the estimation of the strength were reviewed. The formula was expressed by the function of the surface and core hardness and the residual stress.

Many test results for carburized gears and shot-peened gears were surveyed, and the effectiveness of the experimental formula was verified based on the comparison with the surveyed results. If the residual stress was not given, it was approximately evaluated from the hardness. Except for some cases, the proposed formula was verified to be effective for the approximate estimation of fatigue strength of both carburized gears and shot-peened gears.

The enhancement of fatigue strength due to shot peening and electropolishing was quantitatively demonstrated based on the proposed formula. The strength was enhanced about 300 MPa by shot peening of 0.5–0.6 mm arc height. The strength was enhanced still more by electropolishing. The enhancement depended mainly on the residual stress exposed on the surface, and it was about 200 MPa.

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