Effect of Surface Treatments on the Strength of Carburized Gears
— An Application of Fracture Mechanics —

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This paper deals with effects of surface treatment on the bending fatigue strength of SCM415 carburized spur gears. The test gears are treated by the combination of shot peening, chemical polishing and electropolishing after carburization. The fatigue tests demonstrate that the strength is sensitive to the surface condition of tooth fillet and the removal of the non-martensitic layer caused by decarburization is considerably effective in enhancing the strength. In the first part of this paper, the influence of surface treatments such as shot peening, chemical polishing and electropolishing on the strength enhancement for carburized gears are summarized and discussed. In the second part, the crack lengths are calculated from the fatigue test results for the carburized and surface-treated gears, and the effect of surface treatments is discussed from the view point of fracture mechanics.

Key Words : Carburized Gears, Fatigue Strength, Shot Peening, Chemical Polishing, Electropolishing, Surface Treatment, Surface Condition, Crack Lengths, Fracture Mechanics, Strength Evaluation

1. Introduction

In the high load and speed power transmission system, carburized gears are widely used. If power transmission gears are carburized, hardened layer is formed and compressive residual stress increases. Though hardened layer and compressive residual stress are important to the enhancement of bending fatigue strength of gear (Tobe et al., 1986), non-martensitic layer is frequently formed in the heat-treatment process. This layer has low hardness, and thus the bending fatigue strength is reduced by a little due to weakening mechanical properties.

Since the shot peening increases the hardness and compressive residual stress, the bending fatigue strength of carburized and shot peened gears is enhanced much more (Inoue et al., 1989). To design more reliable surface-treated gear, authors have performed fatigue tests and demonstrated the effects of surface treatment on the bending fatigue strength of carburized gear (Lyu et al., 1994).

The fatigue tests also showed that the shot peening as well as the carburization reduced the ductility of the material and that the growth rate was considerably fast in surface layer of the gears. Honda and Conway (1979) and Ahmad and Loo (1977) calculated the stress intensity factor of gear teeth to predict the crack propagation direction. Im et al. (1996) and Song et al. (1996) have investigated fatigue mechanism and strength evaluation.

However, they did not consider the influences of residual stress and hardness layer which are essential and significant for carburized gears. We have also discussed the bending strength of surface-treated carburized gear based on fracture mechanics.

In this paper, the effects of surface treatment and surface conditions on bending fatigue

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strength enhancement for carburized gears are first reviewed. The stress intensity factor for test gear teeth is computed considering the effect of residual stress evaluation method of carburized and shot peened gears (Tobe et al., 1985; Lyu et al., 1994). The effects of surface treatments on bending fatigue strength are clarified from the viewpoint of fracture mechanics by calculating both the threshold length and the endurance length of crack which have been proposed to describe fatigue strength.

2. Effect of Surface Treatment on the Bending Strength

2.1 Heat-treatment

The dimensions and shape of the test gear are shown in Table 1 and Fig. 1, respectively. The gear blanks are made of low alloy steel SCM415. Chemical compositions are indicated in Table 2. The machining and heat-treatment process is presented in Fig. 2. The gear blanks are copper plated and about 20 μm thick to prevent the gear sides from carburizing. This makes the longitudinal characteristics of test gears approximately uniform. Then the gears are hobbed. The gears are finally gas carburized. The carburization and heat-treatment used in this research are common for vehicle gears and no special treatment is given to reduce the decarburization. The effective case depth d_{eff} is about 0.85 mm and it is approximately equal to the depth recommended in the AGMA standard (1983).

Table 1 Dimensions of test gear.

Model	m	[mm]	5
Number of teeth	z		18
Pressure angle		[deg]	20
Finish			Hobbed
Gear grade			JIS 5
Profile modification coefficient			0
Face width		[mm]	8.0±0.01
Tip diameter		[mm]	ϕ100.0±0.01
Span gauger (3 teeth)		[mm]	38.16±0.01
Material			SCM415
Heat-treatment			Carburized
Surface-treatment			see Table 3

Table 2 Chemical compositions of SCM415 [wt.%].

C	Si	Mn	P	S	Cr	Mo
0.165	0.265	0.731	0.015	0.017	1.07	0.151

3.2 Surface treatments of test gears

Three varieties of shot peening conditions are selected for a surface treatment. The arc heights are 0.25 mm, 0.52 mm and 1.02 mm (by Almen strip A) (SAE Standard, 1969). In this paper, these treatments are indicated by the code SP1, SP2 and SP3, respectively. The shots used for each treatment are 0.4 mm, 0.8 mm and 1.2 mm in diameter, and 720 to 740 Hv hardness. The gears

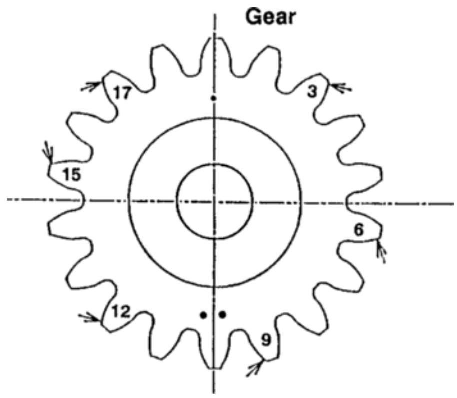

Fig. 1 Shape of test gear.

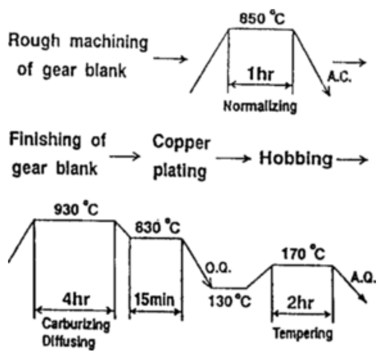

Fig. 2 Machining and heat-treatment process.

Table 3 Surface treatments of test gears.

Code of gears	Surface treatment	Note C: Carburized, $d_{eff}=0.85$ mm
C	Carburized	SP: Shot peening
CSP1	C+SP1	Arc height
CSP2	C+SP2	SP1: 0.25 mm
CSP3	C+SP3	SP2: 0.52 mm
CCP1	C+CP1	SP3: 1.02mm
CCP2	C+CP2	CP: Chemical
CCP3	C+CP3	polishing
CSP2CP1	C+SP2+CP1	EP: Eletropolishing
CSP2CP2	C+SP2+CP2	Removed thickness
CSP2CP3	C+SP2+CP3	CP1: 10 μm
CEP2	C+EP2	CP2: 20 μm
CSP2EP2	C+SP2+EP2	CP3: 30 μm
CCP2SP2	C+CP2+SP2	EP2: 20 μm

Table 4 Surface conditions and fatigue strength.

Code of gears	H_s (Hv)	H_{max} (Hv)	H_c (Hv)	σ_R (MPa)	γ %	R_z μm	σ_u (MPa)
C	540	750	320	−308	21	20.3	761
CSP1	765	840	323	−485	1	14.1	1070
CSP2	797	868	321	−516	1	13.6	1176
CSP3	805	873	326	−426	2	12.9	1148
CCP1	695	760	318	−499	−13.8	985	
CCP2	698	756	320	−496	−	11.1	1009
CCP3	702	759	319	−527	−	10.1	1031
CSP2CP1	793	865	325	−610	−	8.7	1258
CSP2CP2	795	868	324	−694	−	7.5	1318
CSP2CP3	803	863	326	−714	−6.6	1347	
CEP2	705	760	322	−463	−	12.6	965
CSP2EP2	788	870	326	−644	−	11.9	1274
CCP2SP2	805	865	323	−561	−	11.1	1253

Symbol '−' means the value is not evaluated.

are shot peened by 3 times of the exposure time for full coverage, *i. e.*, 300 percent coverage.

To remove the non-martensitic layer, the tooth surface is chemical polished or electro-polished. For chemical polishing, a solution of HF 1 mol/l and H_2O_2 2 mol/l is used. The polishing rate is about 12 μm/min at 40℃. The thickness removed are about 10 μm, 20 μm and 30 μm, and these treatments are indicated by the code CP1, CP2 and CP3, respectively. The code EP2 is used for the electropolishing of 20 μm removal.

After carburizing, the surface of test gears is treated by a combination of the above-mentioned shot peening and/or polishing. The gears are classified into 13 groups according to the treatment. They are indicated by the code which are formed by placing the above-mentioned codes in order of treatment as shown in Table 3.

2.3 Conditions of tooth surface

The surface hardness is considerably increased by shot peening. Measured hardness are summarized in Table 4. The higher the arc height, the larger the hardness increases. The surface residual stress σ_R and the amount of retained austenite γ are also shown in the Table 4. The residual stress is increased about from 120 to 210 MPa by shot peening. In contrast with the hardness increase, the shot peening SP2 is most effective in increasing the residual stress. The residual stress of shot peened gears reaches the maximum at the depth of 50 to 60 μm. Therefore, the higher compressive residual stress is exposed at the surface by chemical polishing and electropolishing after shot peening.

The surface roughness R_Z is improved to a certain extent by shot peening as indicated in Table 4. It is also improved by polishing, therefore, the combination of shot peening and chemical polishing is more effective for surface smoothing. The thickness of the non-martensitic layer of carburized gears determined from the observation, is about 16 μm. The thickness is close to the amount obtained from the hardness distribution and the half value width in the X-ray method. The layer is not very much changed by shot peening, however, it is almost perfectly removed by 20 μm chemical polishing.

2.4 Enhancement of fatigue strength due to surface treatments

The bending fatigue test is performed by using electrohydraulic servo-controlled pulsating testers. The 107 teeth of gears C are tested at nine stress levels to abtain the PSN curves. The test result is shown in Fig. 3. The mean fatigue strength and the standard deviation are obtained as 761 MPa and 63MPa, respectively. From the mean strength and lives, the expression of mean SN curve for the gears C is derived as follows:

$$S=1.55\times10^7(N+5.01\times10^3)^{-1.06}+761 \quad (1)$$

or

$$N=\left(\frac{1.55\times10^7}{S-761}\right)^{0.94}-5.01\times10^3(S\geq761) \quad (2)$$

The mean SN curves for other test gears are determined by the 14 SN test procedure recommended by the JSME Standard(JSME, 1981), and they are shown in Fig. 4.

The strength of chemically polished gears (CCP1-CCP3) is increased by 30 to 35% as compared with the carburized gears C. It is caused by the improvement of surface condition, *i, e.*, the exposure of higher compressive residual stress at the fillet surface as well as the increase in hardness due to the removal of non-martensitic layer. The larger the removal, the higher the fatigue strength.

The strength of shot peened gears(CSP1-CSP3) is also enhanced by 40 to 54%, and the enhancement is greater than that of chemically polished gears. Since the surface residual stress of above-mentioned gears is close to each other as shown in Table 4, the higher strength of shot peened gears might be caused by the surface hardening. The shot peening of 0.52 mm arc height is most effective in enhancing the strength.

The combination of polishing and shot peening (CSP2CP1-CSP2CP3, CCP2SP2, CSP2EP2) is more effective than the single treatment, as expected. The strength is improved by about 65 to 77% as compared with the carburized gears. It is caused by the exposure of higher compressive residual stress, the removal of non-martensitic layer and the improvement of surface roughness.

The highest strength is obtained by the combination of shot peening of 0.52 mm arc height and 20 to 30 μm polishing.

The strength of tested gears is estimated by the experimental formula(Inoue et al., 1989). The estimated fatigue strength is close to the experimental results as indicated in Fig. 5, and the error of estimation is 6% at most. The comparison in detail shows that the fatigue strength of surface polished gears is slightly higher than the esti-

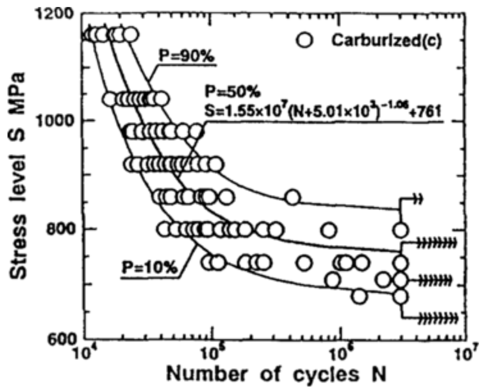

Fig. 3 Fatigue lives and SN curves for gears C.

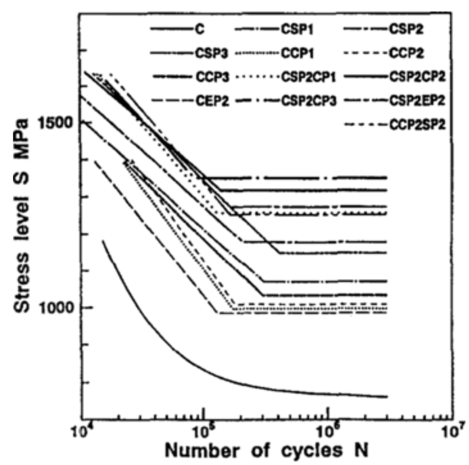

Fig. 4 Mean SN curves of all test gears.

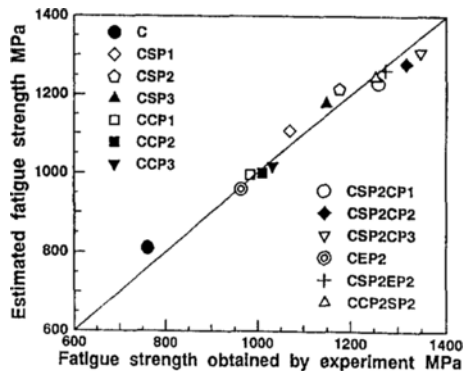

Fig. 5 Estimation of fatigue strength by the proposed formula.

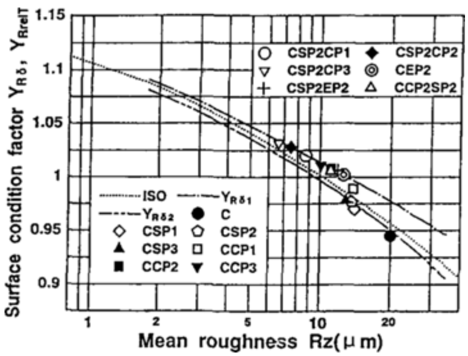

Fig. 6 Surface condition factor.

mated strength, and contrarily, the strength of non-polished gears are a bit lower than the estimation. This might reflect the influence of the surface condition on the strength.

The surface condition, *i, e.*, the roughness and the amount of non-martensitic layer of test gears are not equivalent, neither are the hardness and residual stress. To eliminate the effects of hardness and residual stress on the fatigue strength, they are assumed to be obtained by the proposed experimental formula. The difference between the experimental results and the estimated strength represents the effect of surface condition. Let the ratio of the strength obtained by experiment to the estimated strength be surface condition factor, and be denoted by $Y_{R\delta}$. The factor for every gear is calculated and plotted in Fig. 6 against the surface roughness.

The plots are classified into two groups, that is, the surface polished gears and the non-polished gears. The following expressions are obtained by curve-fitting to the points in these groups.

$$Y_{R\delta 1}=1.40-0.29R_Z^{0.13} \quad \text{(polished)}$$
$$Y_{R\delta 2}=1.22-0.12R_Z^{0.27} \quad \text{(non-polished)} \qquad (3)$$

In Fig. 6, the results are compared with the relative surface condition factor Y_{RrelT} specified in the ISO strength rating formula (ISO/DP 6335/Ⅲ, 1980). The comparison of these factors are not very meaningful, since the gears and their surface conditions are not identical in the test for determinating the factors. However, the value of $Y_{R\delta}$ as well as the variation against the roughness are approximately the same as those of Y_{RrelT}. If the points for non-polished gears in Fig. 6 are shifted right by the amount of non-martensitic layer, they locate approximately on the line for polished gears. It remains unsolved whether the effects of roughness and the non-martensitic layer are additive, and the physical meaning of the sum is vague. However, the result suggests the possibility of adopting a new index, which includes the influences of heat-treatment and surface treatment, for the further discussion of the effect of surface condition.

3. Discussion of Surface Treatment Based on Fracture Mechanics

3.1 Stress intensity factor

The narrow face width and the copper plating on the gear sides make the longitudinal characteristics of the test gears faioly uniform. In fact, the crack fronts observed in the fractured surfaces are almost linear. Therefore, two-dimensional fracture mechanics can be applied to this gear tooth. The stress intensity factor K_I for mode I is calculated by the influence function method (Rice, 1972; Besuner, 1976) as follows:

$$K_I=\int_0^a f(x,\ a,\ geometry)\,\sigma_y(x)\,dx \qquad (4)$$

where $\sigma_y(x)$ is the sum of the bending stress and the residual stress for uncracked tooth, and it is evaluated at the position of crack, perpendicular to the crack. The influence function f for the case of plane strain is represented by the following expression:

$$f=\frac{1}{2}\left(\frac{1-\mu}{E}\cdot\frac{\partial U}{\partial a}\right)^{-1/2}\frac{\partial w}{\partial a} \qquad (5)$$

In this expression, U is the strain energy of the tooth with the crack a for an arbitrary load, and w is the crack opening displacement. E and ν are the modules of elasticity and Poisson's ratio, respectively. The derivatives are numerically evaluated using by the forward differences.

The stress intensity factor for the shot-peened gear of h=0.52 mm is calculated and compared with the carburized gear as well as the gear without residual stress in Fig. 7. The fillet stress of an uncracked tooth is used to express the loading condition, and it is shown as the stress

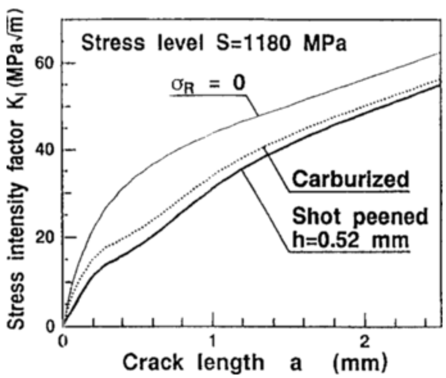

Fig. 7 Effect of residual stress on the stress intensity factor.

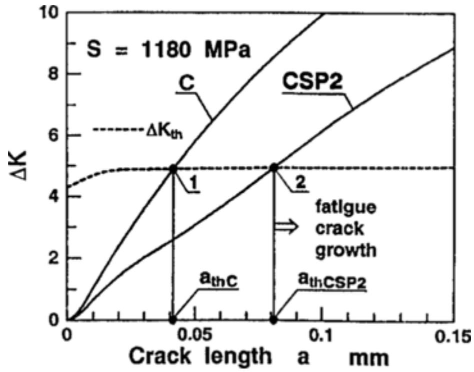

Fig. 8 Estimation of threshold length of crack.

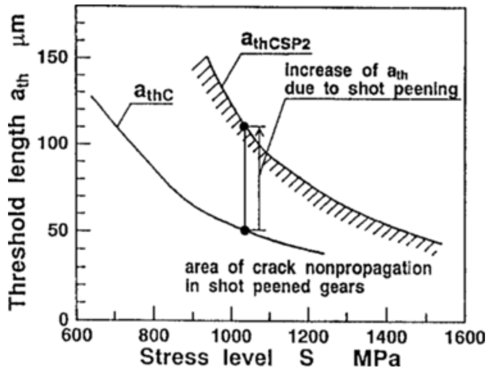

Fig. 9 Threshold length for various stress level.

level S in the figure. The stress level 1180 MPa is slightly higher than the bending fatigue strength of the shot-peened test gear. It is clear that the stress intensity factor is considerably decreased by the residual stress.

3.2 Influence of surface treatments on threshold length of crack

In case a crack exists on the tooth fillet of a gear, the parameter of fracture mechanics ΔK can be calculated from the crack length, stress caused by load and residual stress of tooth fillet. The crack does not propagate if ΔK is less than threshold stress intensity factor ΔK_{th} which is the minimum to cause crack propagation.

$$\Delta K \leq \Delta K_{th} \tag{6}$$

Once the stress distribution is known, Eq. (6) can be written in terms of the crack length a and the critical crack length a_{th}.

$$a \leq a_{th} \tag{7}$$

Here, ath is the threshold length of crack corresponding to ΔK_{th}. An estimation method for the threshold length of crack is illustrated in Fig. 8. In the case of the load S=1180 MPa, the stress intensity factor ΔK of mode I is evaluated. The stress intensity factor of gear CSP2 in Fig. 8 is smaller than that of gear C because it has higher compressive residual stress. The threshold stress intensity factor range ΔK_{th} can be expressed as a function of hardness (Kato et. al., 1993) which is calculated from the hardness distribution of the carburized gear. It is illustrated by the broken line in Fig. 8. The intersecting point 1 in Fig. 8 gives the crack length which means that ΔK of carburized gear is equal to ΔK_{th}. It is also called the threshold length of crack a_{thC}. The intersecting point 2, which is computed in the same way, gives the threshold length of crack a_{thCSP2}. The threshold length can be presented in the following form.

$$a_{th} = f(S, \sigma_R, \Delta K_{th}) \tag{8}$$

For the same material and loading condition, a_{th} depends only on the residual stress. The higher the compressive residual stress, the longer the threshold length of crack. If the load is larger than the stress level as shown in Fig. 8, the crack which is larger than ath propagates. The increase in threshold length of crack from point 1 to point 2 is caused by residual stress effect. Therefore, as can be seen in Fig. 8, the threshold length of crack increased about 40 μm by shot peening. For various stress levels, crack threshold length of C

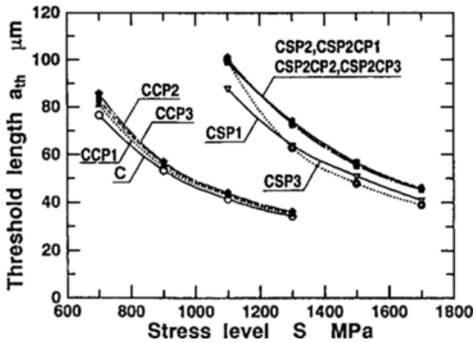

Fig. 10 Threshold length of crack for surface treated gears.

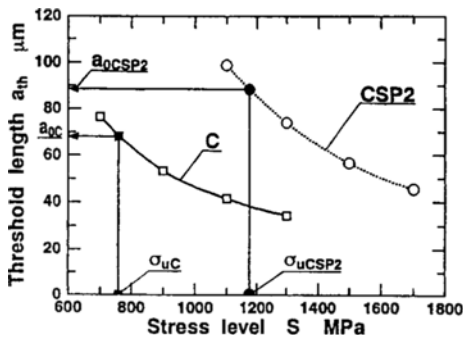

Fig. 11 Estimation of endurance length of crack

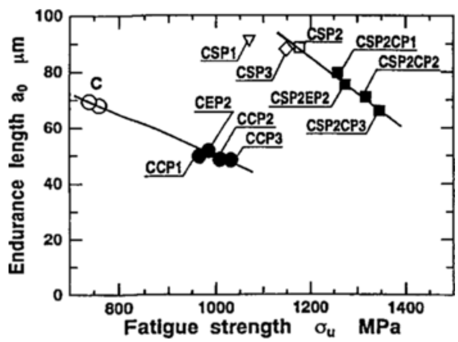

Fig. 12 Endurance length of crack.

gear and CSP2 gear is shown in Fig. 9. The hatched area under the line of a_{thsp2} indicates the crack nonpropagation area for shot peened gear. The increase in a_{th} represents the residual stress effect caused by shot peening.

The crack threshold length for the surface-treated gears is evaluated for various stress levels and illustrated in Fig. 10. They are divided into two groups. One is carburized and polished gears, and the other is shot peened gears. The carck threshold length of shot peened gear is larger than that of the carburized gear at the same load level. This is due to the difference in the residual stress.

As can be seen in Eq. (7), the increase in a_{th} implies the strength improvement. The fact that surface treatment is effective in strength improvement can be explained from the viewpoint of fracture mechanics.

3.3 Influence of surface treatments on endurance length of crack

Usually fatigue life can be divided into two processes. One is initiation process and the other is propagation process of fatigue crack. But as it is difficult to consider the initiation process of fatigue crack, only propagation process of crack is taken into consideration in this paper. The critical initial crack length is obtained for the loading for endurance limits and it is called the endurance length of crack and denoted by a_0 in this paper. Since the gears are designed normally for this loading condition, the endurance length is substituted in the crack length in the above criterion, as given by.

$$a_0 < a_{th} \tag{9}$$

As explained above, the initiation process of fatigue crack is not considered, therefore, the endurance length of crack a_0 is not a real crack length but a crack length by extending the calculation of crack computed propagation to crack creation process. Thus a_0 is a parameter concerning crack creation process. The endurance length of crack a0 is influenced by heat-treatment and surface conditions of materials but it does not depend on the gear geometry except for size effect. Namely the relation between a_{th} and a_0 corresponds to the relation between calculated stress and allowable stress. The load satisfying expression Eq. (9) provides safe load.

The estimated a_0 is shown in Fig. 11. The endurance crack length is obtained from the intersecting point of fatigue strength σ_u and the line of a_{th}. The evaluated endurance length are shown in Fig. 12. They are still in two groups, and the shorter endurance length indicates the higher bending strength. Consequently a_0 decreases almost linearly and it is proportional to the increase in fatigue strength. Therefore a_0 is decreased by surface treatments and the decrease in a_0 implies strength improvement.

4. Conclusion

The bending fatigue tests were performed to clarify the effect of surface treatments such as shot peening, chemical polishing and electropolishing on the strength enhancement of carburized gears.

The effects of surface treatment on the bending fatigue strength were discussed from the view point of fracture mechanics, and the crack threshold length and endurance length were introduced for the discussion. This results can be summarized as follows:

(1) Surface treatment improved fatigue strength in all cases. Especially it was most effective in the case of chemical polishing about 20 ~30 μm after shot peening. Strength improved about 580 MPa which is 1.77 times as high as carburized gear.

(2) The stress intensity factor for the shot-peened gear was rather smaller as compared with that for the carburized gear because of the effect of residual stress.

(3) The crack threshold length a_{th} increased due to surface treatment. Particularly when the gears were shot peened, it increased compressive residual stress, and this caused crack threshold length a_{th} about 40 μm longer than carburized gear.

(4) The influence of surface treatment on a_0 was evaluated and discussed. The effect of surface treatments on the strength enhancement was expressed by the decrease in a_0.

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