$N_{cc} \fallingdotseq (1/3)N_o$ when $i_A = 8$, where N_{cc} is the power flowing through the belt section.

Reference

(1) Morozumi, M., Theory and Calculation Method for Design of Planetary Gears and Differential Gears, (in Japanese), Nikkan-Kogyo-Shinbun-Sha (1989), pp.33–39

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Fatigue Strength Analysis of Carburized Transmission Gears*

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Dimensions	Small gear	Large gear
Module	1.5	
Pressure angle (deg)	17.5	
Helix angle (Direction)	34 (Right)	34 (Left)
Number of teeth	33	41
Pitch circle (mm)	59.701	74.182
Width of teeth (mm)	13	15
Center distance (mm)	67	

Table 1 Dimensions of test gears

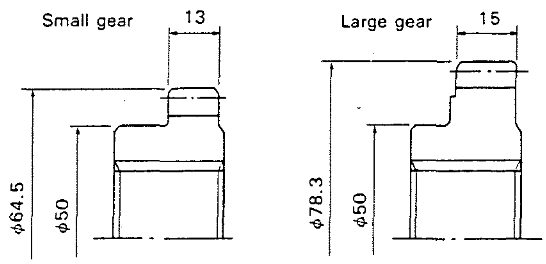

Fig.1 Test gear

Grade	C	Si	Mn	P	S	Ni	Cr	Mo
JIS SCr420H	0.19	0.26	0.82	0.022	0.021	0.05	1.11	0.02
JIS SNCM420H	0.19	0.20	0.59	0.024	0.015	1.74	0.49	0.20
JIS SCr430H	0.31	0.24	0.75	0.016	0.018	0.02	1.05	0.01
High Ni-Mo steel	0.19	0.10	0.30	0.008	0.012	2.00	0.31	0.75

Table 2 Chemical compositions of test steels (wt%)

1. Introduction

Improving the fatigue strength of gears is important for compatibility with rising of engine power, and for miniaturization and lightness of transmission units. Generally, carburized helical gears are used for automobile transmissions. Nevertheless, there are many unclear points in the relationship between fatigue strength and material factors.

Therefore, this report investigates the effects of material factors such as intergranular oxidation, alloying elements, etc., and the effect of shot peening, by examining the fatigue strength of carburized helical gears which are manufactured from various low-alloy steels and different manufacturing processes, and additionally investigates the behavior of fatigue cracks.

2. Experimental method

The details of test gears are shown in Table 1. and Fig. 1. Moreover, the chemical composition of test steels is shown in Table 2.

After machining, these gears were carburized and tempered. As the carburizing methods, general gas-carburizing and vacuum-carburizing were mainly carried out to investigate the influence of intergranular oxidation on gear fatigue strength, and shot peening was carried out at the archheight of 0.4-0.5mmA.

In this research,bending fatigue strength at 1×10^5 cycles of these gears was mainly found by using a torque-circulation gear-tester.

Moreover, to account for the behavior of the fatigue cracks of carburized gears, i.e. the crack's initiation life and the state of its proopagation during gear tests, the presence or absence of fatigue cracks and their length were investigated by discontinuing the fatigue tests at the fixed rotation cycle before the rupture of test gears. Moreover, the observation of cracks was done with an optical microscope after the cutting of gears.

3. Results and consideration

Fatigue test results for the correlation of material and fatigue strength are shown in Table 3. The results of fatigue tests revealed that intergranular oxidation, alloying elements and heat treatment processes have little effect on fatigue strength, and that shot peening is the most effective method for obtaining high-strength gears.

Furthermore, to account for the correlation between fatigue stength and material factors, regression analysis was conducted. Proportion (R^2) found by regression analysis is shown in Table 4. As a result of this, the peak value of residual compressive stress contained inside or the integral value of residual stress measured in inward direction (defined as being to 0.4mm from the surface) showed a greater degree of correlation with the fatigue strength of carburized gears, which is the fatigue strength at 1×10^5 cycles, than the residual stress value at the surface where failure originated. Moreover, these values were found by measuring residual stress distribution by X-ray diffraction. However, it was so difficult to measure the distribution at tooth root that it was measured at the cylindrical outside surface close to the teeth.

Therefore, the whole residual compressive stress field is considered to have a strong influence on fatigue strength. The peak value of residual compressive stress and the integral value of residual stress inside were increased by shot peening.

In connection with the investigation of fatigue crack behavior, to investigate the influence on it of increasing residual compressive stress by shot peening, peened and unpeened gears made of JIS SCr420H were used. The conditions of investigating cracks are shown on S-N curve in Fig.2. Input power was chosen

Confirmation items		Purpose	Effect* (%)	Judgement
Steels (alloy elements)	JIS SNCM420H	Improvement of toughness	0	=
	JIS SCr430H	Increase in inside hardness of tooth root	+3	=
	High Ni-Mo steel**	Improvement of toughness	+15	=***
Heat treatment	Vacuum-carburizing	Prevention of intergranular oxidation	+3	=
Shot peening		Increase in residual compressive stress	+18 — +28	++
Others	Decrease of effective case depth (from 0.4mm to 0.2mm at tooth root)	(Improvement of toughness)	+15	+

* Rate of fatigue strength increase (at 10^5 cycles) relative to the gas-carburized gear made of JIS SCr420H
** The gear made of this steel had lower effective case depth than other gears, such as 0.2mm at tooth root. (Other gears' effective case depth is over 0.4mm.)
*** It was judged that the reason for increased fatigue strength was not added alloy elements, but lower effective case depth.

Table 3 The summary of fatigue test results

Material factor	Proportion (R^2) Unpeened	Proportion (R^2) Peened
Surface hardness at 0.1mm depth. (HRC)	0.1896 (Y = −1.28X + 2586)*	0.0003 (Y = −19.0X + 1883)
Internal hardness of tooth root. (HRC)	0.0362 (Y = −2.60X + 1543)	0.2469 (Y = −11.5X + 2219)
Effective case depth. (0.2−0.6mm) (mm)	0.3593 (Y = −521X + 1637)	0.6063 (Y = −721X + 2067)
Surface residual stress in lead direction at tooth root. (MPa)	0.4529 (Y = −0.60X + 1478)	
Peak value of residual compressive stress. (MPa)	0.8748 (Y = −0.57X + 1277)	
Integral value of residual stress in depthwise direction (MPa)	0.8567 (Y = −3.44X + 1169)	

* Regression equation
Y: Fatigue strength at 10^5 cycles (MPa)

Table 4 Correlation between fatigue strength and material factors

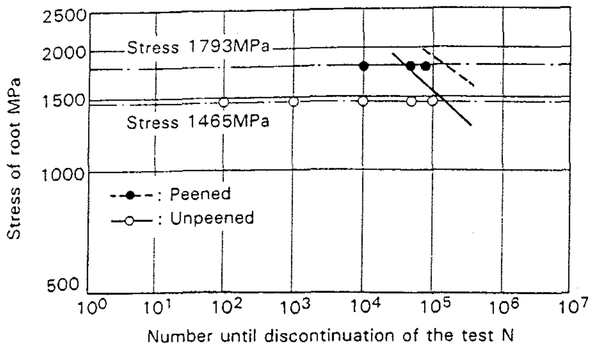

Fig.2 Test conditions of investigating cracks shown on S-N curve

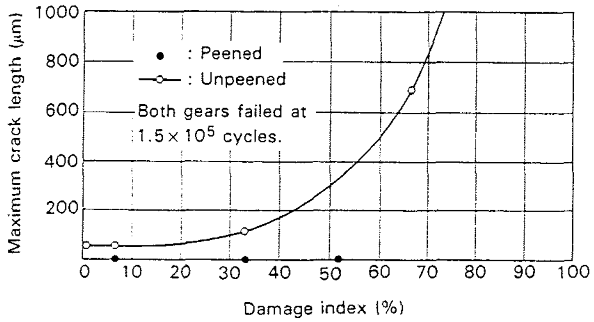

Fig.3 The state of crack propagation

as both failure lives becoming the same. The investigation results of crack behavior are shown in Fig.3. The abscissa axis of Fig.3 is the damage index, which is the ratio of power input number to failure life.

As a result of this, in the case of unpeened gears, it was revealed that the fatigue crack is generated in the early stage of fatigue at 0.1% or less damage index and it does not appreciably progress until 30% damage index is reached. At present, the reason why fatigue cracks are generated in this early stage of fatigue life is considered to be intergranular oxidation. Neverthless, it is supposed that crack initiation life has little influence on failure life in the case of unpeened gears, because vacuum-carburizing, which generates no intergranular oxidation at the gear surface, gives no improvement in the fatigue strength of gears.

On the other hand, in the case of shot peened gears, no crack was found at 50% damage index. As a result of this, the whole of the residual compressive stress field is considered to retard crack occurrence, at least in the range of observation by optical microscope. However, the details of fatigue crack behavior are left to further research.

4. Conclusions

An analysis was made of the fatigue strength and fatigue crack behavior of carburized helical gears of 1.5 module manufactured from various low-alloy steels by different manufacturing processes.

The conclusions reached in this research are the following:

(1) Improvement obtained in the fatigue strength of carburized gears by changing materials and heat treatment processes is slight. Neverthless, the most effective method of improvement of gear fatigue strength is shot peening.

(2) Residual compressive stress correlated well with gear fatigue strength. Moreover, its peak value or integral value measured in inward direction showed a greater degree of correlation with fatigue strength than the residual stress value at the surface where failure originated.

(3) The outline of the fatigue crack behavior of carburized gears was revealed. Neverthless, more particular analysis is required to research the influence of residual stress on crack behavior, because there are still some unclear points in this aspect.

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