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Study on Methodology to Increase Fatigue Limit of Gears

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1 Introduction

At present, improvement of the fatigue limit of automotive components is a top priority. The demand is especially high for automobiles due to the environmental and fuel economy expectations. To improve the fatigue limit of automotive components, the following three methods are currently in common use: (i) Minimize surface roughness, (ii) Increase the hardness of the material, (iii) Introduce a large compressive residual stress at the surface. Item (iv) is an extremely adequate method; therefore, a close attention is being paid to achieve a minimized surface roughness at this time. Although item (ii) is a reasonable method, it is difficult to apply to the automobile gears and springs with hardness as high as 600–700 HV. Fatigue limit ($\Delta\sigma_w$) is proportional to hardness up to 400–500 HV. Above 500 HV, $\Delta\sigma_w$ does not increase with hardness, but decreases as hardness increases. Therefore, it is not appropriate to increase hardness further for components such as gears and springs. Item (iii) is a general method and shot peening is used widely. However, it is extremely difficult to introduce a large compressive residual stress by shot peening since the hardness of automotive components reaches 600–700 HV. To solve above problems and improve the fatigue limit of automotive components, the authors conducted a study focusing on the following points: (a) What is the process of fatigue fracture and what is the resistance factor in each stage? (b) What stress ratio (R) can be applied to automotive components? (c) Why does the fatigue limit start decreasing when hardness reaches some level? Is there any way by which the decrease can be inhibited? (d) How can a large compressive residual stress be introduced to a material with 700HV or more? As a result of this study, it was found that the number of components subjected to cyclic loading with positive stress ratios ($R > 0$) is unexpectedly high among automotive components such as gears and springs. Therefore, after working closely on the above four points concentrating on the $R > 0$ components, the following results for improvement of the fatigue limit were proposed: (1) Increase the hardness of materials as high as possible. (2) Introduce compressive residual stress as high and deep as possible. (3) Decrease the grain size as much as possible. (4) Grind the surface region of components to remove early stage fatigue damage such as extrusion and intrusion, and stage I fatigue crack. (5) Heal the stage I fatigue crack during service if possible [1]. In this paper, the fatigue limit range of a gear was improved considerably, simply and economically, using above methods (1), (2) and (3) together.

2 Fatigue Process and Resistance Factor to Fatigue Fracture

The process of fatigue fracture is introduced in many references [2]. According to these references, the process of fatigue fracture consists of the following seven steps: (1) Cyclic stress below yield stress activates the dislocations. (2) The activated dislocations then create a slip band inside a grain. (3) Extrusions and intrusions are formed near the surface region. (4) A stage I fatigue crack is formed along the intrusion and then propagates through few grains. (5) The stage I crack is then transformed to a stage II fatigue crack by cyclic tensile stress. (6) Propagation of the stage II fatigue crack. (7) Final fracture. In the above seven steps, promoting and resistance factor for fatigue damage of each step were considered systematically as shown in Table 1. The promoting factor of early stage of stage I crack is a cyclic shear stress. And to resist the damage and the crack propagation, it is important to increase the hardness as high as possible and to make the grain size as fine as possible. The promoting factor of stage II crack is a cyclic tensile stress. To increase the resistance of the stage II crack propagation, it is important to introduce a large compressive residual stress. Tange et al. [3] showed that it is very important to increase the compressive residual stress at the surface in fine grained steel. From the statements above, it can be concluded that using a combination of the following methods improves the fatigue limit of the components subjected to $R > 0$ loading: (1) Maximizing the yield stress (the hardness). (2) Introducing a large and deep compressive residual stress. Introducing a large compressive residual stress at the surface improves the fatigue strength especially for fine grained steel. (3) Decreasing the grain size as much as possible.

Table 1: Promoting and resistance parameter for fatigue damage at each stage

	Step	Promotive parameter	Resistance parameter		
			Yield stress (Vickers hardness)	Grain size	Compressive residual stress
Stage I crack	(1)	Shear stress	◎	◎	×
	(2)	〃	◎	◎	×
	(3)	〃	◎	◎	×
	(4)	〃	×	◎	◎
Stage II crack	(5)	Tensile stress	×	×	◎
	(6)	〃	×	×	◎
	(7)	〃	×	×	◎

◎:contribute considerably, ×: have no relation

3 Application to Test Gears

3.1 Materials, Samples and Test Method

Two kinds of steels were used in this study. Chemical compositions (wt.%) of these steels A and B are; C: 0.19, 0.51, Si: 0.06, 0.20, Mn: 0.84, 0.74, P: 0.010, 0.02, S: 0.019, 0.02, Ni: 0.09, 0.04, Cr: 0.11, 0.11, Cu: 0.09, 0.08 and Mo: 0.4, 0.0, respectively. Both steels were quenched and tempered to a hardness level of 200 HV. Then, they were machined to a gear (module: 3, number of teeth: 36, helix angle and hand: 17° right hand, pressure angle = 14°30', over-ball diameter: 123.6 mm). Six kinds of gears were made. Gears I-IV were made of steel A while the gears V and VI were made of steel B. The surface treatment techniques adopted are Vacuum

Carburizing (VC), Contour Induction Hardening (CIH) and Double Shot Peening (DSP). After machining, the gears were surface-treated with these combined treatments. Table 2 shows the combined surface treatments for each gear. For example, gear IV was first vacuum carburized, then contour induction hardened and finally double shot peened. The gears I-IV were first vacuum carburized to C = 0.8 wt.%. The vacuum carburizing conditions were: pressure in furnace = $6.67 \cdot 10^{-2}$ kPa, temperature = 1223 K, atmosphere = C_3H_8 gas, carburizing time = 2.88 ks. After being carburized, the gears were cooled to 1173 K and subsequently quenched using N_2 gas of $5 \cdot 10^2$ kPa. The gears III–VI were induction hardened. The contour induction hardening conditions were: 3 kHz frequency for pre-heat, 1000kW power for pre-heat, 150 kHz frequency for main-heat and 600 kW power for main-heat. Two kinds of shots were used: Ø0.6 mm shot for primary peening and Ø0.08 mm shot for secondary peening. Using shot sizes in this sequence is the key to introduce an appropriate compressive residual stress near the surface in the gear [4]. The hardness of both shots is 700 HV. Peening conditions were: 490 kPa and 392 kPa air pressure, 0.35 mmC and 0.26 mmN arc heights, respectively. Details of the shot peening parameters and their effects are explained in [4]. To measure the residual stress and the volume fraction of the retained austenite (γ_R), a micro X-ray stress measuring apparatus was used. The gear surface was masked with Ø5 mm window, and was polished to a specified depth using electrolytic polishing method. The X-ray conditions are: Cr-K_α beam X-ray spectrum and 0.3 mm X-ray beam injection diameter. The fatigue testing was done using an electro-hydraulic testing machine at a stress ratio of $R = 0.1$, 10 Hz frequency and sine wave load cycle in air.

Table 2. Gears and combined surface treatment

Gear	I	II	III	IV	V	VI
Steel	A	A	A	A	B	B
Surface Treatment	VC	VC+DSP	VC+CIH	VC+CIH+DSP	CIH	CIH+DSP

3.2 Retained Austenite

Fig. 1 shows the distribution of γ_R. The open diamond symbol shows γ_R of gear I. The γ_R at the surface is 11.5 % and the maximum γ_R is 26.8 %. The solid square symbol shows γ_R of gear II. The γ_R at the surface is very low (1.8 %) and the maximum one is 16.5 %. The γ_R of gear II was reduced considerably as compared to gear I. This γ_R reduction is attributed to double shot peening. The γ_R of gear III is shown by the open triangle symbols in Fig. 1. The γ_R at the surface and the maximum are 24.5 % and 31.3 %, respectively, showing extremely high values. γ_R of gear IV at the surface and the maximum values are 3.4 % and 21.2 %, respectively. Similar to gear II, γ_R of gear IV was reduced drastically meaning that the retained austenite was transformed to martensite by strain transformation caused by DSP.

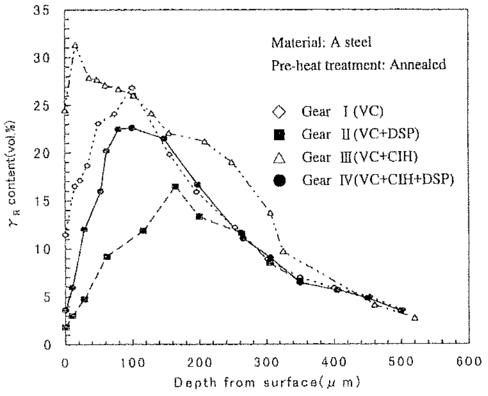


Figure 1: Depth profile of retained austenite (γ_R) in the roots of the gear teeth.

3.3 Residual Stress– Depth Profiles

Fig. 2 shows the residual stress distribution of gears I-IV. The open diamond symbols show the residual stress distribution of gear I with the compressive residual stress at the surface (σ_s) of about 300 MPa and the maximum compressive residual stress (σ_{max}) of about 400 MPa, respectively. Both values are not so high. Solid square symbols show the residual stress distribution of gear II. σ_{max} was introduced at the surface with a value of 1838 MPa. The value of σ_{max} is surprisingly high. Open triangles show the residual stress distribution of gear III. The σ_s and σ_{max} are 801 and 1054 MPa, respectively. In gear IV, the maximum residual stress was also introduced at the surface with a value of 1862 MPa. Even 300 μm below the surface, a very high compressive residual stress of 900 MPa was measured. Extremely high residual stresses were introduced in gears II and IV for the following reason: the retained austenite was transformed to

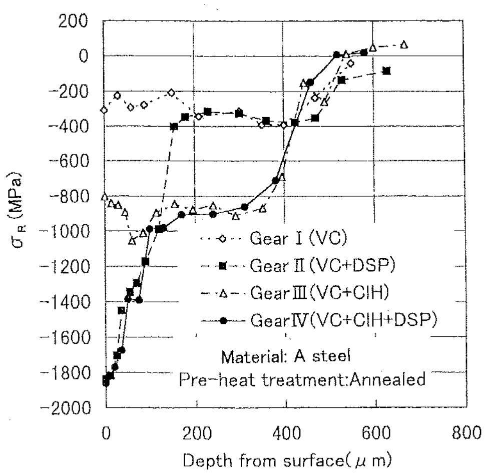


Figure 2: Depth profiles of residual stresses (σ_R) in the roots of the gear teeth.

martensite by DSP, resulting possibly in a quite large compressive residual stress. In gear V, σ_s and σ_{max} values are only 662 and 810 MPa, respectively. In gear VI, values of σ_s and σ_{max} are 1159 and 1346 MPa, respectively. These compressive residual stresses are much higher than those of gear V. The only possible reason for high compressive residual stress in gear VI is that retained austenite was transformed to martensite by strain transformation caused by DSP. No retained austenite was present in gear V. On the other hand, compressive residual stresses in gear VI were not very high compared with those in gear IV. The occurrence of transformation made this difference in residual stress values.

3.4 Hardness–Depth Profiles

Fig. 3 shows the hardness–depth profiles in gears I–IV. The open diamonds and triangles symbols show the hardness distribution of gears I and III, respectively. The highest hardness of gears I and III are 799 HV and 893 HV, respectively. However, the highest hardness of gears II and IV are 1040 and 1067 HV, respectively, showing much higher hardness than those of gears I and III. These results are attributed to the strain induced martensite transformation as previously mentioned. The highest hardness of gear V is 757 HV. The highest hardness of gear VI is 792 HV. The maximum hardness of gear VI is 35 HV higher than that of gear V. This result can be attributed to the work hardening by DSP.

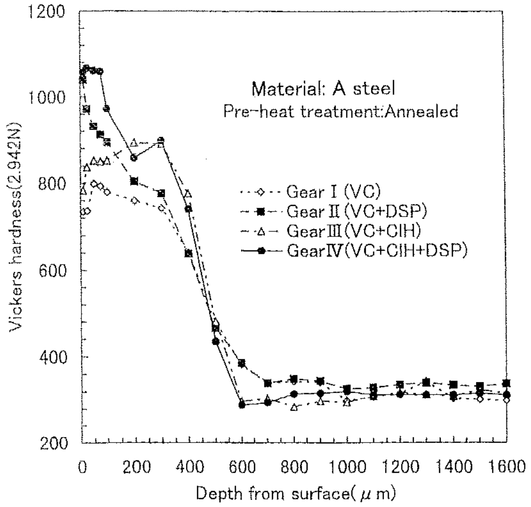
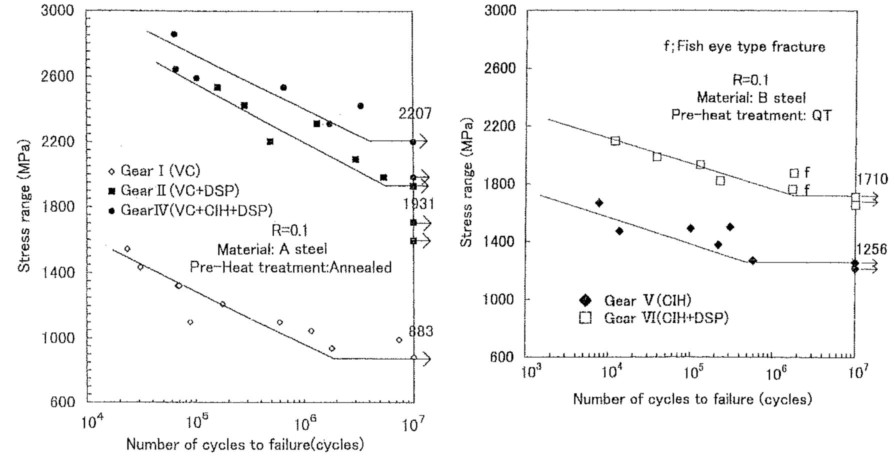


Figure 3: Vickers hardness (HV)–depth profiles in the roots of the gear teeth.

3.5 Fatigue Strength

Fig. 4a shows S-N curves of the gears I, II and IV. The open diamonds, solid squares, solid circles show the S-N data of gears I, II and IV, respectively. The gear III was not fatigue tested. The stress range at the fatigue limit $\Delta\sigma_w$ of gear I is 883 MPa, while that of gear II achieved an increase of about 118 % up to 1931 MPa, and a further increase of 150 % to 2207 MPa was realized with gear IV. These surprising increase in the fatigue limit are attributed to the following two reasons: (a) The carbon content at the surface of these gears is about 0.8 % and the retained austenite near the surface was reduced considerably by strain induced martensite transformation. (b) The hardness near the surface is over 1000 HV, thus, the material has high resistances to initiation and propagation of stage I fatigue cracks. Fig. 4b shows S-N curves of gears V (solid triangles) and VI (solid circles). The stress range of the fatigue limit $\Delta\sigma_w$ of gear V is 1256 MPa, while that of gear VI is increased by 38 % to 1710 MPa. Both gears showed similar hardness. It can be said that the difference in the fatigue limit resulted from the different compressive residual stress distribution of both gears. The conclusion is that double shot peening played a key role in increasing the fatigue limit.



a) Gear I, II and IV

b) Gear V and VI

Figure 4: S-N diagram of gears

3.6 Regression Analysis of the Fatigue Strength

The fatigue tests were conducted on 8 kinds of gears by these authors. All tests were performed under $R = 0.1$ loading. To understand the important factors to increase the fatigue limit, a regression analysis was made using the above 8 data with special attention to the following three parameters: (a) Yield stress converted from Vickers hardness (HV). (b) Maximum compressive residual stress σ_{max}. (c) Grain size d_γ.The information required for the regression analysis (HV, σ_{max} and d_γ) of 5 gears out of 8 is included in this paper. The yield stress σ_Y was estimated from HV: $\sigma_Y = 3.27$ HV (MPa).

Fig. 5 shows correlation between $\Delta\sigma_w$ and $\{0.478\,(\sigma_Y + \sigma_{max}) + 1.363 d_\gamma^{-1/2} - 894\}$.

From Fig. 5, it can be seen that $\{0.478\,(\sigma_Y + \sigma_{max}) + 1.363 d_\gamma^{-1/2} - 894\}$ is an important parameter to increase fatigue limit. $\Delta\sigma_w$ is given by the following equation

$$\Delta\sigma_w = 0.478\,(\sigma_Y + \sigma_{max}) + 1.363\, d_\gamma^{-1/2} - 894 \quad (1)$$

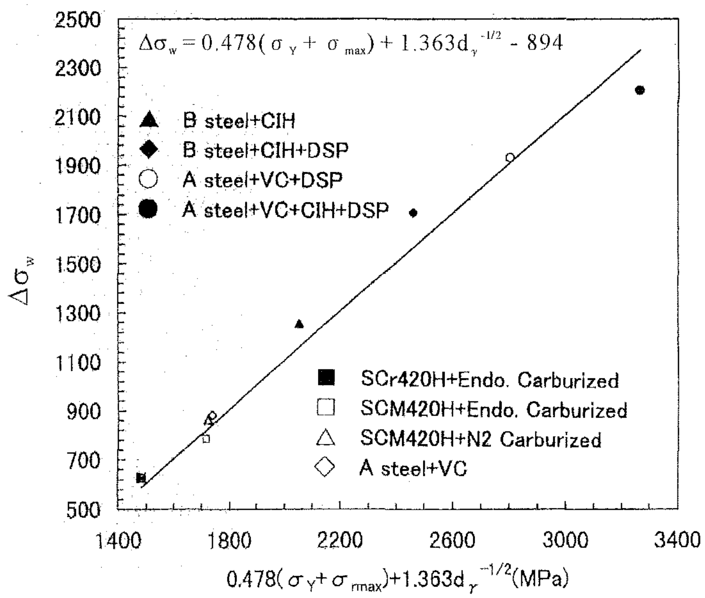


Figure 5: Regression analysis of experimental fatigue data.

and this parameter shows good agreement with our proposal (1) to (3) in the chapter 2 for increasing fatigue limit.

4 Conclusions

To increase the fatigue limit of car components, fatigue processes were analyzed and new methodology for increasing fatigue limit was proposed. To achieve an increase in fatigue performence, combined surface treatments were applied to the gears. These treatments were: Vacuum Carburizing (VC), Contour Induction Hardening (CIH) and Double Shot Peening (DSP). Using these treatments, the following results were obtained:

(1) With VC, the carbon density at the surface was increased up to 0.8 wt.%, and grain boundary oxidation was completely prevented.

(2) With CIH, the grain size was refined to about 5 μm.

(3) With DSP, most of the retained austenite near the surface was transformed to martensite, resulting in increased hardness up to 1067 HV and extremely high compressive residual stresses.

(4) With the above combined effects, the stress range of the fatigue limit ($R = 0.1$) was increased up to 2207 MPa.

(5) The stress range of the fatigue limit of gears $\Delta\sigma_w$ is given by the equation (1) as a function of yield stress, the maximum compressive residual stress and the average grain size. This result shows good agreement with the new methodology proposed in this paper based on the fatigue process analysis.

5 References

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