Examination of Surface Hardening Process for Dual Phase Steel and Improvement of Gear Properties†

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Abstract:

The dual phase steel was developed for improvement of fatigue strength and decrease in heat treatment distortion. The chemical compositions, formation of microstructure, carburizing properties, and influence of ferrite area fraction on heat-treatment distortion was discussed. Additionally, improvement of fatigue strength with optimizing of surface hardening process was examined. As a result, pitting fatigue strength was improved by 29% compared with conventional one. The breakdown is; change in steel 9%, change in heat treatment condition (vacuum atmosphere and nitrogen added) 12%, and addition of double shot peening 7%.

1. Introduction

Because machinability[1)] is important simultaneously with strength in gears used in the transmissions and suspensions of automobiles and construction equipment, the majority of gears used in these applications are manufactured by a process of forging and machining followed by surface hardening by carburization, using case hardening steels such as JIS SCr420, SCM420, SCM822, etc. (JIS: Japanese Industrial Standards).

In recent years, higher strength in these gears has been strongly desired from the viewpoints of weight reduction and downsizing. In automotive applications, heat-treatment distortion of gears has also become a problem due to demand for reduced noise[2)].

JFE Bars & Shapes developed "dual phase steel"[3,4)] for transmission and suspension gears with the aims of achieving high strength while also reducing gear noise by minimizing distortion of the gears during carburizing, considering low-noise (quietness) performance.

This paper describes the features of "dual phase steel," together with the results of an examination of optimization of the surface hardening process using this steel with the aim of improving the fatigue strength of gears.

2. Characteristics of Dual Phase Steel

2.1 Merits of Dual Phase Steel

Dual phase steel has the following three merits.

(1) The existing manufacturing processes and lines can be used without major modifications.

(2) The rejection rate and gear tooth profile correction work can be reduced as a result of reducing heat-treatment distortion.

(3) Fatigue strength is comparable to that of conventional steels.

Dual phase steel is a material which was designed so as not to require a special manufacturing line or processes or large changes in the conventional manufacturing process, and thus does not require changes in the manufacturing process or processing conditions. Furthermore, because heat-treatment distortion in carburizing is minimized in comparison with conventional steels, a reduction in the rejection rate can be expected. In cases where tooth profile correction work had conventionally been performed by tooth surface polishing or other processes in the manufacturing line, it is also

† Originally published in *JFE GIHO* No. 23 (Mar. 2009), p. 24–29


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possible to omit those processes. Dual phase steel also has carburizing properties comparable to those of conventional steels, and provides fatigue strength equal or superior to that of the conventional steels.

2.2 Chemical Composition and Carburizing Properties

Table 1 shows an example of the chemical composition of dual phase steel in comparison with that of JIS SCM420 equivalent material. The following points may be mentioned as distinctive features of the chemical composition of dual phase steel.

(1) A dual phase carburized internal microstructure is obtained by addition of Si and Mo.

(2) Hardenability is controlled by adjustment of Mn and Cr.

Si and Mo are elements which elevate the Ac_3 transformation point. When the Ac_3 transformation point is elevated, it becomes possible to produce a dual phase microstructure of austenite (hereinafter, γ) and ferrite (hereinafter, α) in the carburized internal microstructure at the quenching temperature used in conventional carburizing. This reduces the amount of martensite transformation, which is accompanied by volumetric expansion during post-quenching, making it possible to reduce heat-treatment distortion. Although a decrease in hardness can be expected if ferrite precipitates in the interior, the increase in ferrite hardness achieved by using the ferrite solution hardening function of Si compensates for this decrease in hardness.

Microstructure formation during carburization of the dual phase steel will be explained using **Fig. 1**. When a conventional case hardening steel is carburized under the carburizing conditions used formerly, heating is performed up to the γ single phase region during carburizing heating. Following this, the temperature is reduced slightly and quenching is performed. However, even at the quenching temperature, the γ single phase microstructure is maintained in all regions from the vicinity of the surface layer, where the carbon content has been increased by carburization, to the interior, where the carbon content is the same as that of the base material. A single phase of γ also exists in all parts of the dual phase steel during carburizing. However, due to its higher transformation point, when the temperature is reduced to the quenching temperature, the non-carburized area in the interior enters the dual phase region of α and γ, and as a result, α remains untransformed, even though γ undergoes the martensite transformation during quenching. Thus, as a distinctive feature of the dual phase steel, transformation expansion is relaxed by reducing the martensite transformation in the interior region, thereby reducing heat-treatment distortion.

Photo 1 shows the microstructures of the dual phase

Table 1 Example of chemical compositions of dual phase steel

(mass%)

Steel	C	Si	Mn	Cr	Mo	Nb
Dual phase steel	0.21	1.43	0.43	0.61	0.78	0.021
JIS SCM420	0.21	0.21	0.76	1.10	0.18	—

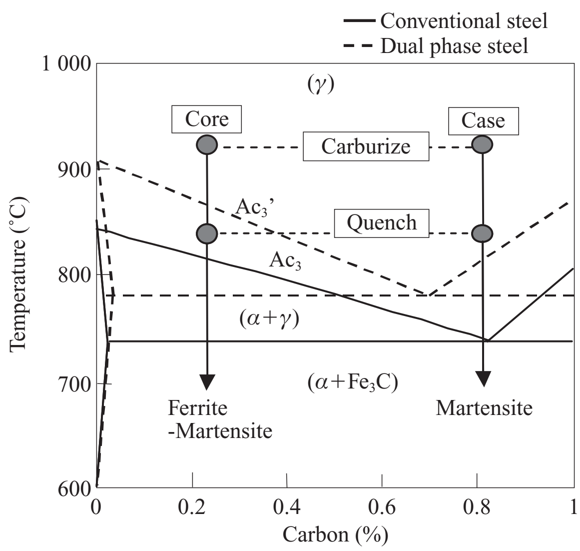

Fig. 1 Phase transformation of dual phase steel during carburizing

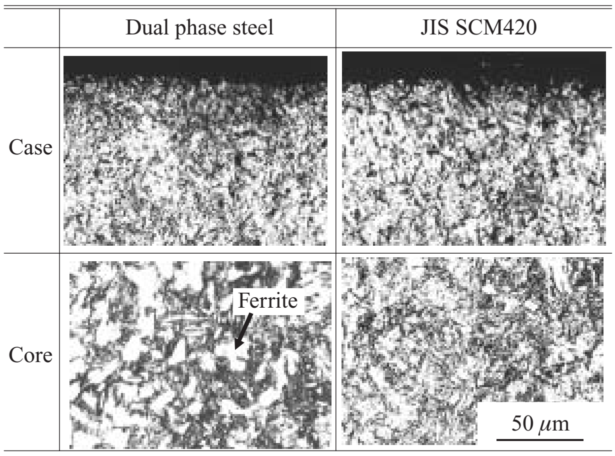

Photo 1 Microstructures of carburized and quenched dual phase steel

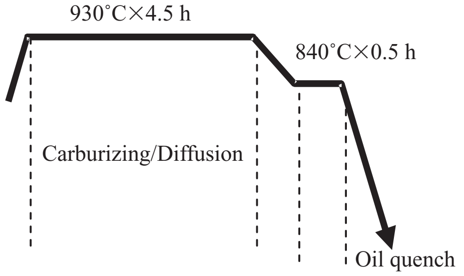

Fig. 2 Carburizing condition (Temper: 160°C × 2 h)

steel and SCM420 after carburizing, when carburizing was performed under the conventional conditions (**Fig. 2**). In the microstructure of the dual phase steel, the region which was carburized to a high carbon content in the same manner as SCM420 is a martensite single phase microstructure; however, in the internal microstructure, ferrite is dispersed in the martensite matrix.

Figure 3 shows the change in the depth of the grain boundary oxidation layer when the amount of Si addition was changed, using the dual phase steel composition in Table 1 as the base composition. The grain boundary oxidation layer shows its maximum depth when Si addition is 0.25%. With larger addition than this, the layer displays a tendency to become shallow. **Photo 2** shows the difference in the grain boundary oxidation layer with 0.25% Si steel, which displays the peak grain boundary oxidation layer depth, and 1.5% Si steel, which is the dual phase steel. In comparison with the 0.25% Si steel, the oxidation layer is shallower in the 1.5% Si steel. Furthermore, although oxidation progresses along the grain boundaries in the 0.25% Si steel, in contrast to this, oxidation in the 1.5% Si steel progresses both at the grain boundaries and inside the grains. It may also be noted that enrichment of Si could be observed in these oxidized parts.

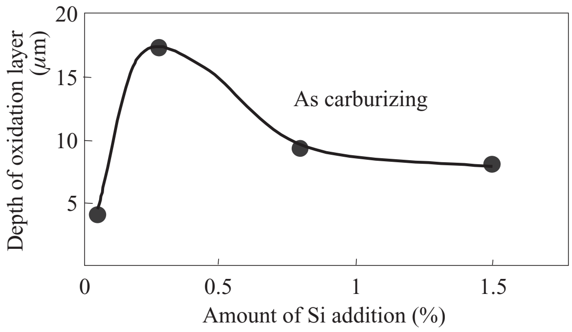

Fig. 3 Change in grain boundary oxidation layer depth with Si content

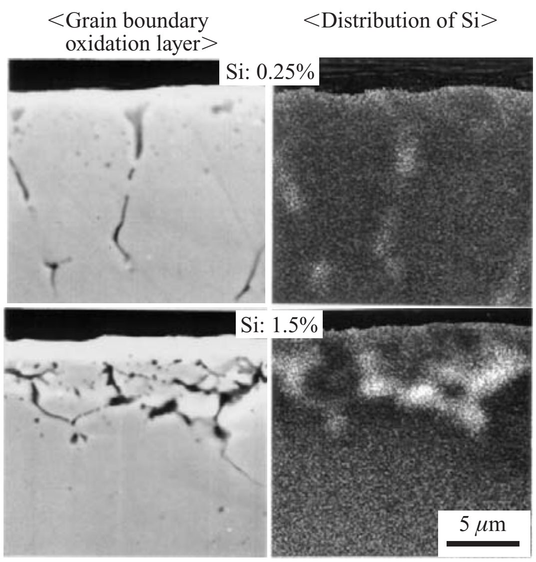

Photo 2 Difference in grain boundary oxidation with Si content

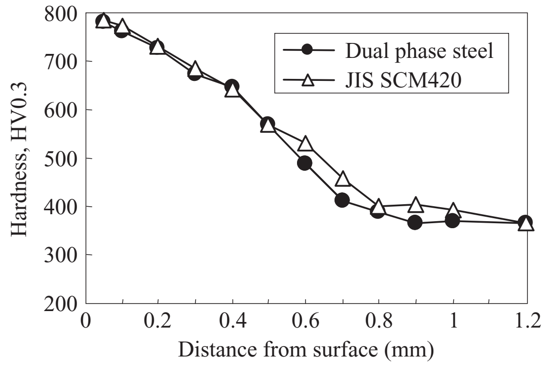

Fig. 4 Hardness distribution after carburizing and quenching

Figure 4 shows the hardness distribution after carburizing of the dual phase steel and conventional case hardening steel. Because the hardenability of the dual phase steel was adjusted to be equal or higher than that of the conventional case hardening steel, there is no difference in the hardness distribution of the carburized parts of the two steels. With the dual phase steel, although ferrite precipitated in the interior, adequate hardness was obtained by securing hardenability and solution hardening of the ferrite phase by Si.

2.3 Heat-Treatment Distortion by Carburizing

Figure 5 shows the difference in the amount of distortion before and after carburizing of the dual phase steel and conventional case hardening steel. The change in the aperture area before and after carburizing was investigated using the test piece shown in the figure. With both steels, the amount of distortion shows a tendency to increase accompanying increases in hardness, in other words, increases in hardenability. However, it can be understood that the amount of distortion in the dual phase steel has been reduced to less than half in comparison with the conventional steel.

Figure 6 shows the effect of the internal ferrite area fraction on heat-treatment distortion of the dual phase

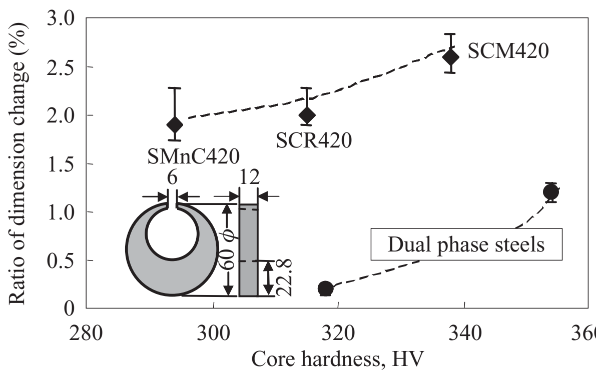

Fig. 5 Distortion by carburizing and quenching

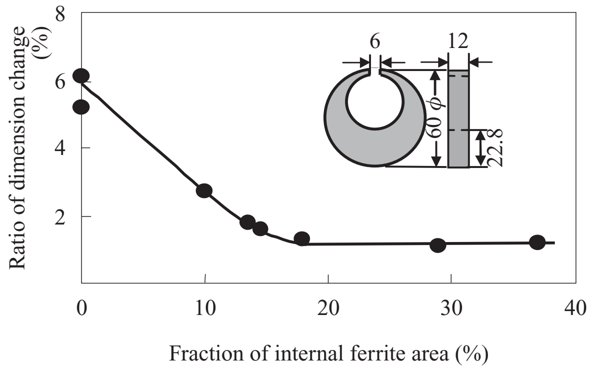

Fig. 6 Relationships between heat treatment distortion and internal ferrite area fraction

steel. The amount of distortion decreases as the internal ferrite area fraction increases, but distortion becomes constant when the area fraction exceeds 15%. Based on this, in order to suppress heat-treatment distortion of the dual phase steel, the internal ferrite area fraction should be set at 15% or higher.

3. Achievement of High Strength in Gears by Surface Hardening

3.1 Suppression of Fracture

Fatigue fracture of gears can be broadly divided into bending fracture of the tooth root and pitting fracture of the tooth surface. However, accompanying service conditions characterized by high contact pressure, gear life is frequently determined by pitting fracture.

Initiation of cracks in pitting fracture is considered to take the following two forms. In the first, the crack initiates from an area of reduced strength at the tooth surface, whereas, in the second, the crack initiates from an area of reduced strength directly under the surface, where Hertz stress reaches its maximum.

In conventional carburizing using converted gas, oxygen exists in the carburizing atmosphere. For this reason, the grain boundaries at the gear surface are embrittled by oxidation of Si, Mn, Cr, and other component elements with high oxygen binding power[5], and as a result, cracks easily initiate from the oxidized parts of the grain boundaries[6]. Based on this, suppression of grain boundary oxidation appears to be the most important issue for preventing initiation of surface cracks. Furthermore, tensile stress is also applied to the surface as a result of sliding between pairs of tooth surfaces, which occurs simultaneously with contact between the teeth. Increasing compressed retained stress appears to be effective for reducing this stress.

In rolling surfaces, low temperature tempering occurs directly under the surface due to the temperature increase caused by contact between pairs of gears[7]. When martensite which contains a high content of carbon as a result of carburizing is tempered at low temperature, it decomposes into ε carbides and cementite. As a result, the carbon content is reduced and softening occurs in the surrounding area. In cases where few crack initiation sites exist at the surface, for example, due to grain boundary oxidation, etc., it is conceivable that fracture may occur as a result of cracks initiating from the softened part directly under the surface, which is subjected to the maximum Hertz stress.

In order to prevent crack initiation directly under this surface, it is important to suppress temper softening. For this, it is necessary to add temper softening suppressing elements to the steel. Increasing the content of dissolved nitrogen is also considered to be effective for suppressing temper softening[8].

3.2 Fatigue Strength under Optimum Conditions

In this research, the methods which appeared to be most effective for increasing the fatigue strength of gears were examined, focusing on the surface hardening process. **Table 2** shows the chemical composition of the dual phase steel (DP) used in this study and SCM822H as a comparison material. In order to improve the fatigue strength of the dual phase steel, a composition design with increased amounts of Si and Cr as low temperature temper softening suppressing elements was adopted.

Figure 7 shows the heat treatment conditions in the vacuum carbonitriding process. In order to suppress grain boundary oxidation at the surface, vacuum carburizing was examined in this research as an alternative to the conventional carburizing process using converted gas. In addition, temper softening was suppressed by increasing the content of dissolved nitrogen, which was accomplished by performing nitriding after carburizing. The carburizing temperature and tempering temperature

Table 2 Chemical compositions of steel for fatigue test

(mass%)

Steel	C	Si	Mn	Cr	Mo	V	Ac_3 (°C)
DP	0.23	1.75	0.42	1.52	0.38	0.15	899
SCM822	0.22	0.25	0.75	1.15	0.36	—	816

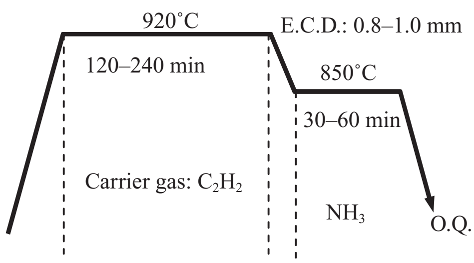

Fig. 7 Condition of vacuum cabonitriding process (Temper: 160°C × 2 h)

were the same as in the conventional process.

Next, shot peening was performed in order to impart compressed retained stress and thereby suppress crack initiation at the surface. **Table 3** shows the shot peening conditions. In this research, air nozzle-type hard shot peening[9], which has a high projection velocity, was adopted in order to impart compressed retained stress most effectively, and double shot peening was performed, in which shot of the same diameter as in the conventional process were used in the first stage, followed by shot peening with small diameter shot in the second stage.

With the dual phase steel, a roller pitting test was performed after these surface hardening processes. **Figure 8** shows the specimen and test conditions. On the other hand, with the comparison steel SCM822H, the roller pitting test was performed using a specimen which had received only conventional gas carburizing.

Figure 9 shows the test results. With the SCM822H, treatment was limited to gas carburizing, which is the conventional surface hardening process. In contrast to the results in that case, an improvement of approximately 29% in the fatigue limit could be observed when vacuum carbonitriding was performed on the dual phase steel, followed by double shot peening.

Table 3 Shot peening condition

Condition	Conventional S.P.	Double S.P.	
		1st	2nd
Projection speed	Slow	Fast	Fast
Diameter of shot	0.8 mm	0.8 mm	0.08 mm
Hardness of shot	52–57 HRC	60 HRC	60 HRC
Arc height	0.52 mmA	0.82 mmA	0.32 mmA
Coverage	over 300%	over 300%	over 300%

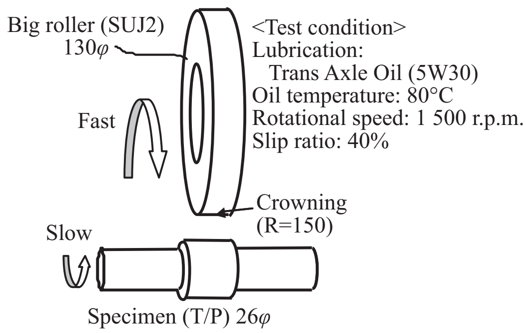

Fig. 8 Roller pitting test condition

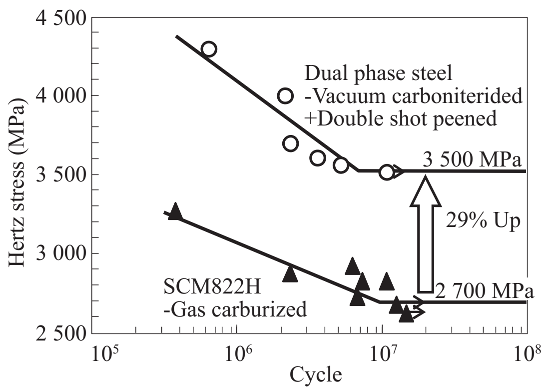

Fig. 9 Effect of steel class and surface hardening process in roller pitting test

3.3 Examination of Factors in Improvement of Fatigue Strength

The contributions of various factors to improvement of fatigue strength when the surface hardening process was optimized using the dual phase steel were examined based on the results of the investigation conducted previously.

Figure 10 shows the softening property (temper softening resistance) when low temperature tempering was performed. The dual phase steel shows temper hardness values approximately 100HV higher than those of SCM822H at both 300°C and 400°C. Furthermore, with the dual phase steel, an increase in hardness of approximately 100HV can be observed at temperatures of both 300°C and 400°C as a result of performing nitriding simultaneously with carburizing. From this, it can be estimated that changing the steel from SCM822H to the dual phase steel and performing nitriding have approximately equal effects in improving fatigue strength.

Figures 11–13 show the results of roller pitting tests performed in the past.

Figure 11 shows the results of a test of the dual phase steel, with which vacuum carbonitriding and double shot peening were performed, in comparison with SCM822H. The dual phase steel shows a 9% improvement in the fatigue limit in comparison with SCM822H.

Figure 12 shows results comparing gas carburized SCM822H and gas carbonitrided dual phase steel. A 15% improvement in the fatigue limit was observed as a result of using the dual phase steel as the steel in combination with addition of nitrogen.

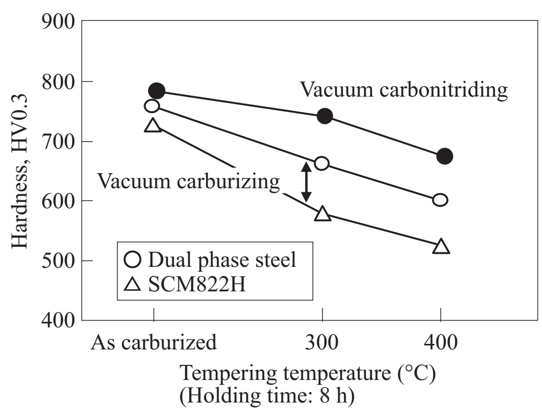

Fig. 10 Characteristics of the temper softening resistance

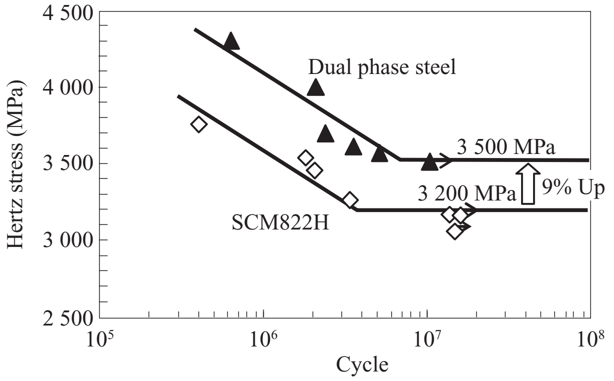

Fig. 11 Effect of steel class in roller pitting test (vacuum carbonitrided and double shot peened)

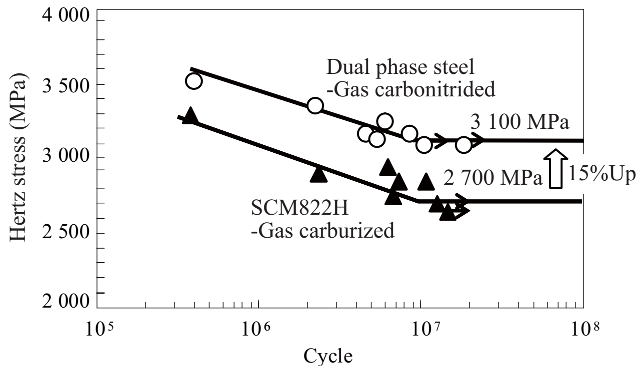

Fig. 12 Effect of steel class and nitriding in roller pitting test

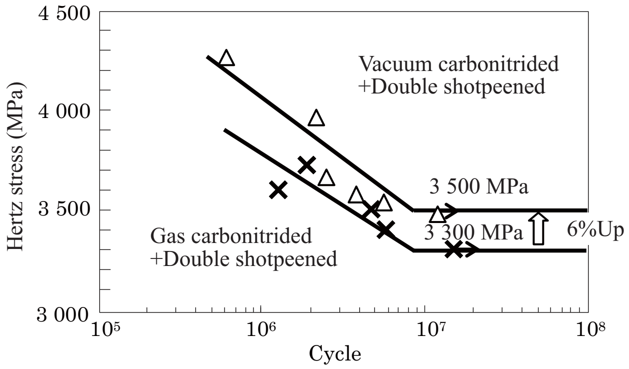

Fig. 13 Effect of atmosphere of carbonitriding in roller pitting test (Dual phase steel)

Figure 13 shows a comparison of the performance of the dual phase steel with gas carbonitriding followed by double shot peening, and with vacuum carbonitriding followed by double shot peening. **Photo 3** shows the condition of formation of the grain boundary oxidation layer for the respective specimens. With the material which was subjected to heat treatment under a gas atmosphere, a grain boundary oxidation depth of approximately 7 μm was observed. In contrast to this, grain boundary oxidation did not occur in the specimen which was subjected to vacuum carbonitriding, and the fatigue strength of this material was 6% higher than that of the gas-treated material.

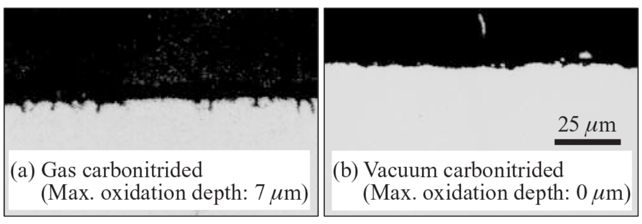

Photo 3 Effect of atmosphere on grain boundary oxidation

Figure 14 shows the roller pitting fatigue strength of the dual phase steel in specimens which were subjected to gas carbonitriding or vacuum carbonitriding, followed in both cases by double shot peening. The fatigue limit was improved by approximately 13% by changing the atmosphere from gas to a vacuum and performing double shot peening. The improvement of fatigue strength by shot peening is considered to be largely attributable to the effect of increasing the compressed retained stress in the vicinity of the surface layer. As shown in **Fig. 15**, the compressed retained stress at the outermost surface layer is approximately 300 MPa higher with the double shot peening applied in this research than with the ordinary single shot peening

Table 4 shows the results when the factors contributing to the improvement of fatigue strength and their respective contributions were arranged based on the above study. Here, 9% of the improvement in fatigue strength was attributed to the change of the steel type, and 12% was attributed to the change of the surface

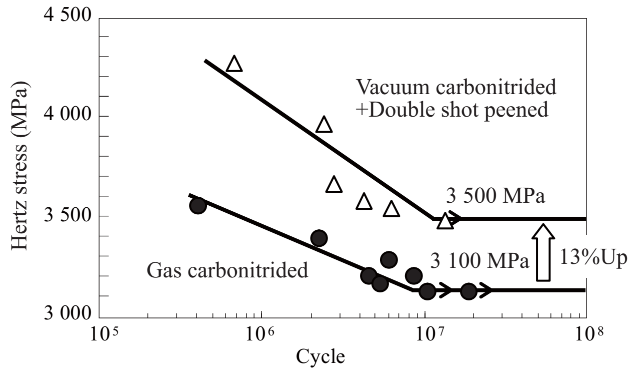

Fig. 14 Effect of atmosphere of carbonitriding and shot peening (Dual phase steel)

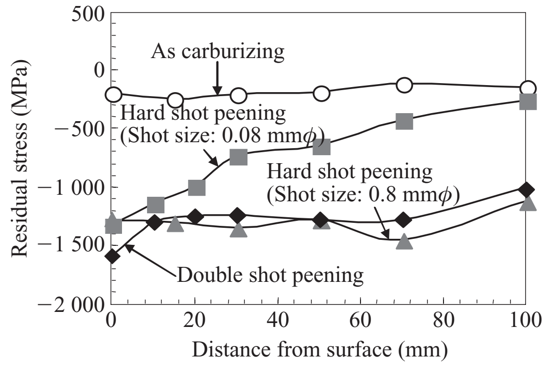

Fig. 15 Difference in residual stress distribution with shot peening change (Dual phase steel)

Table 4 Each effect to improve pitting fatigue strength

Measures	Effect to improve pitting fatigue strength	Remarks	
Change of steel	9%	Fig.11	Fig.12 (15%)
Nitrogen added	6%	15%-Fig.11	
Vacuum atmosphere in heat treatment	6%	Fig.13	Fig.14 (13%)
Double shot peening	7%	13%-Fig.13	

hardening process from the conventional gas carburizing to vacuum carbonitriding. As the breakdown for the change of processes, the contribution of changing the atmosphere to a vacuum was 6%, and that of the nitriding process was also 6%. A 7% improvement in fatigue strength was attributed to double shot peening.

4. Conclusion

An examination of optimization of the surface hardening process using a recently-developed dual phase steel was carried out with the aims of improving fatigue strength and reducing heat-treatment distortion. The following results were obtained.

(1) An improvement of 29% in pitting fatigue strength was obtained in comparison with the conventional SCM822H gas-carburized material by using the dual phase steel and optimizing the surface hardening process.

(2) Of the 29% improvement in pitting fatigue strength, 9% was attributed to the improvement effect of changing the steel from SCM822H to the dual phase steel.

(3) A 12% improvement effect was obtained by changing the surface hardening process from the conventional gas carburizing to vacuum carbonitriding. In addition, fatigue strength was improved by 7% by performing double shot peening.

With the dual phase steel, low heat-treatment distortion also has the effect of suppressing tooth surface runout. However, this effect was not examined in the present work. Considering the durability of actual gears, further improvement in fatigue strength by this low heat-treatment distortion technology is expected.

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