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,) and ferrite (hereinafter,) 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 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 [illegible]

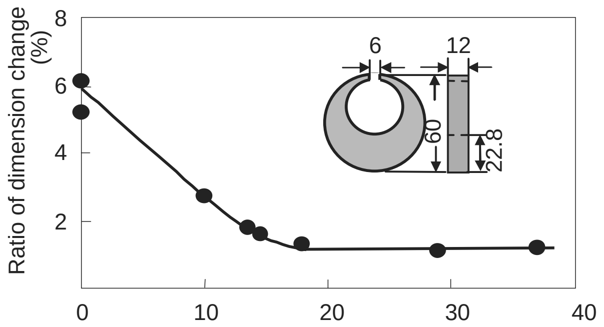

Fig. 6 Relationships between heat treatment distortion and internal ferrite area fraction

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 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

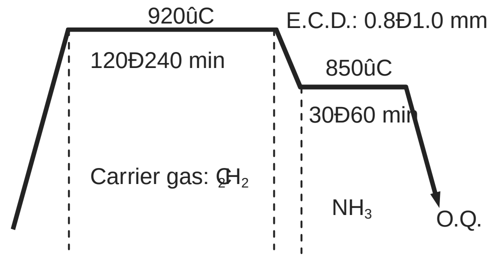

Fig. 7 Condition of vacuum cabonitriding process (Temper: 160°C × 2 h)

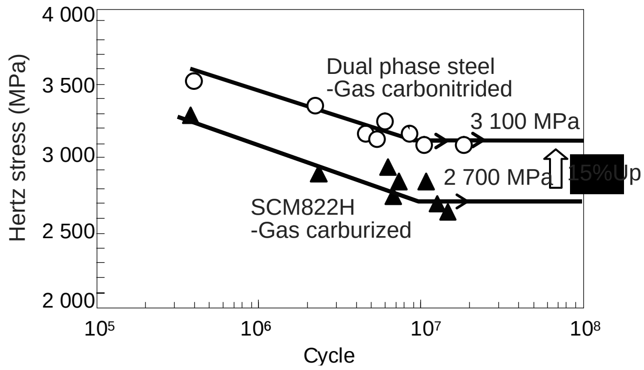

Fig. 12 Effect of steel class and nitriding in roller pitting test

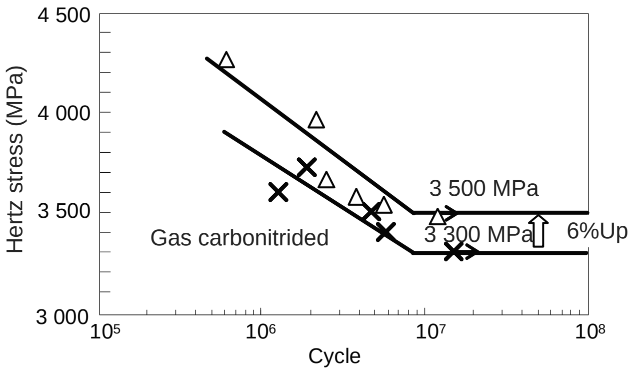

Figure 13 shows a comparison of the performance of the dual phase steel with gas carbonitriding followed by double shot peening, and with vacuum carbonitriding followed by double shot peening. Photo 3 shows the condition of formation of the grain boundary oxidation layer for the respective specimens. With the material which was subjected to heat treatment under a gas atmosphere, a grain boundary oxidation depth of approximately 7 m 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.

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

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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