

Development of γ' -Fe₄N Phase Control Technology and Low-Carbon Alloy Steel for High-Strength Nitrided Gear

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ABSTRACT

A new nitriding technology and material technology have been developed to increase the strength of microalloyed gears. The developed nitriding technology makes it possible to freely select the phase composition of the nitride compound layer by controlling the treatment atmosphere.

The treatment environment is controlled to exclude sources of supply of [C], and H₂ is applied as the carrier gas. This has made it possible to control the forward reaction that decomposes NH₃, helping to enable the stable precipitation of γ' -phase, which offers excellent peeling resistance. A material optimized for the new nitriding technology was also developed. The new material is a low-carbon alloy steel that makes it possible to minimize the difference in hardness between the compound layer and the substrate directly below it, and is resistant to decline in internal hardness due to aging precipitation in the temperature range used in the nitriding treatment. The combination of these developed technologies has increased gear strength more than 50% against conventional gas-nitrocarburized products.

This research also determined that the peeling resistance of the compound layer changed with the thickness of the compound layer and the ratio between γ' -phase and ϵ -phase in the compound layer. This relationship with the thickness of the compound layer indicated that it would be possible to realize equivalent surface fatigue strength to carburizing treatments by controlling thickness. As a result, it was possible to realize equivalent surface fatigue strength to carburizing treatments while maintaining the characteristic of low and stable deformation offered by nitriding treatments.

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INTRODUCTION

The reduction of CO₂ emissions has become a major focus for the contemporary automotive industry, and demand is increasing for technologies to increase fuel efficiency and other environmentally friendly technologies. The transmission gears are the cores of the automotive power transmit mechanism, and a variety of efforts are being made in this area to increase strength, with the intention of reducing the size and weight of the gears.

Carburizing is the method normally applied in order to achieve high levels of strength in transmission gears, but this method results in martensite transformation, and because of the shape of the gears, heat treatment can produce significant deformation that has a negative effect on the accuracy of the tooth profile, which becomes a factor in gear noise. This therefore entails increased cost due to the necessity, from considerations of commercial appeal, for additional processes such as tooth surface grinding and circularity correction to realize the desired tooth profile. By contrast, gas-nitrocarburizing

does not result in martensite transformation. Deformation due to heat treatment is minimal, and deformation is stable, making it a simple matter to realize an accurate tooth profile. However, strength is low in comparison to carburized parts. It has therefore been necessary to deepen the hardened layer in conventional nitrocarburizing treatments in order to increase strength, leading to increased treatment time and increased cost. There is also an issue of peeling of the nitride compound layer that precipitates as the surface layer. A more fundamental approach to the resolution of these issues is therefore necessary.

This research discussed in this paper discovered that the controlled deposition of a γ' -phase in the nitride compound layer, previously characterized by an ϵ -phase, dramatically increased the peeling resistance of the compound layer, and developed a nitriding technology that controlled the deposition of the γ' -phase. In addition, the development of a new material that would make it possible to exploit the developed nitriding technology to the greatest extent possible helped to enable the realization of an equivalent level of surface fatigue strength in nitrided gears as in carburized parts. This paper will discuss these new technologies, in addition to considering the relationship between strength and the ratio of the γ' -phase and the ϵ -phase in the precipitated compound layer.

1. DEVELOPMENT AIMS

Carburized low-alloy steels are generally used in the manufacture of transmission gears from consideration of factors including machinability, fatigue strength, and wear resistance [1], [2]. However, because this involves a heat treatment that results in a phase transformation, significant variations in deformation necessitate correction of the tooth profile. Given the fact that they produce a low and constant deformation, numerous developments have focused on gas nitrocarburizing technologies, which use lower-temperature heat treatments than carburizing technologies [3], [4]. However, because the nitride compound layer that forms at the surface of the material in these treatments lacks ductility [5], [6], it is not possible to avoid peeling of the type shown in [figure 1](#) in sliding or striking environments, and the achievement of an equivalent level of strength to carburized parts has been challenging [7], [8].



Figure 1. Peeling damage to S35C nitrocarburized gear

In order to achieve the high level of strength demanded for gears, the research discussed in this paper therefore developed a countermeasure against peeling of the nitride compound layer, in addition to a new material technology. The characteristics sought by the research were as follows:

1. An equivalent or higher level of surface fatigue strength to standard carburized parts;
2. An equivalent low and constant level of deformation to conventional gas-nitrocarburized parts;
3. A level of material hardness that took machinability into consideration.

2. REALIZATION OF HIGH-STRENGTH NITRIDE COMPOUND LAYER

2-1. Atmosphere-Controlled Nitriding

In conventional gas-nitrocarburizing treatments, an iron-nitride compound layer termed a ϵ -phase is formed on the surface of the material. [figure 2](#) shows the results of an electron back-scattering pattern (EBSP) analysis of the phase distribution in a compound layer formed by conventional gas-nitrocarburizing on S35C. Based on these results, conventional gas-nitrocarburizing treatments can be judged ineffective as an approach to realizing peeling resistance because they form a single ϵ -phase characterized by coarse rod-shaped crystal grains and also form a porous layer on the surface layer. In addition, the ϵ -phase displays a hexagonal close-packed (HCP) crystal structure. Because this structure prioritizes basal sliding, the crystal structure can be considered to be brittle and to resist deformation. Given this, the present research focused on the γ' -phase crystal structure in a Fe-N binary phase diagram. The γ' -phase displays a face-centered cubic (FCC) crystal structure and has 12 slip systems, and the crystal structure can therefore be considered to possess considerable toughness. Based on these considerations, it was decided that a high level of surface fatigue strength could be obtained through the use of the γ' -phase, and a nitriding treatment technology that would form a γ' -phase was developed.

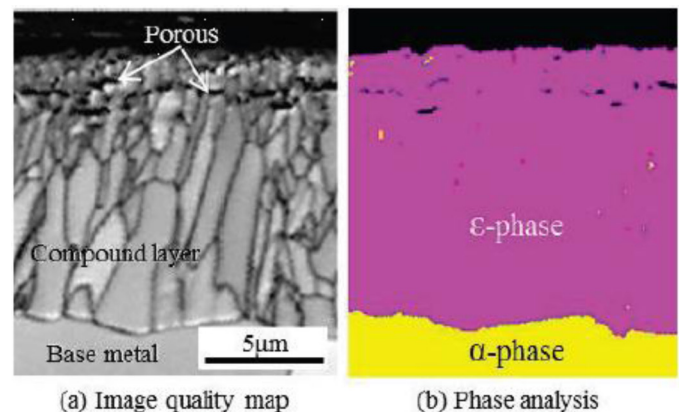


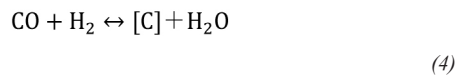
Figure 2. EBSP analysis of compound layer produced by conventional gas nitrocarburization (S35C)

Lehrer et al. [9] have reported on the reaction mechanism of standard nitriding treatments. The nitriding reaction occurring in the furnace can be expressed by [Equation \(1\)](#), and the nitriding potential (K_N below) can be defined by [Equation \(2\)](#).



$$K_N = P_{NH_3} / (P_{H_2})^{3/2} \quad (2)$$

[N] is active nitrogen that contributes to the nitriding reaction. Lehrer et al. indicate that control of the value of K_N makes it possible to select whether an ϵ -phase layer, a γ' -phase layer, or no compound layer is formed [9]. This indicates that in order to realize the desired γ' -phase, it would be necessary to reduce the value of K_N below that in the conventionally employed conditions, which precipitate an ϵ -phase [9]. Based on Equation (2), it would be possible to reduce K_N by reducing the amount of NH_3 added or increasing the amount of hydrogen. The formulas for the carburizing reaction in conventional gas-nitrocarburization are normally as follows:



[C] is active carbon that contributes to carburization reaction during gas-nitrocarburization. The 848[K] cross-section of the Fe-C-N ternary phase diagram [10], shown in figure 3, shows the effect of [C] on phase transformation, indicating that the addition of a miniscule amount of [C] would result in the precipitation of an ϵ -phase. It was therefore necessary to exclude sources of supply of [C] from the nitriding atmosphere in order to stably precipitate a γ' -phase.

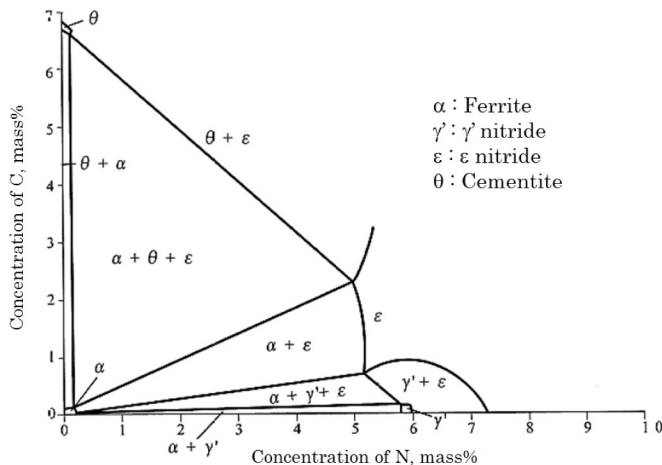


Figure 3. Fe-C-N ternary phase diagram at 848K

It was therefore decided that the technology under development would apply a nitriding method that excluded any source of supply of [C] from the gas atmosphere. The reaction formula under these conditions would be equivalent to Equation (1). Because Equation (1) is a reversible reaction, when N_2 is used as the carrier gas, a forward reaction proceeds until the degradation of NH_3 reaches a steady state. This means that in order to maintain a low K_N value for the precipitation of a γ' -phase during the nitriding reaction, it is necessary to minimize the amount of NH_3 added to the greatest extent possible. This makes the margin for NH_3 management extremely narrow, rendering practical control impossible. To respond to this issue, the authors used H_2 as the carrier gas. With the addition of H_2 , the initial state in the furnace becomes NH_3 and H_2 . Because of this, while the

reaction equation is the same as Equation (1), the fact that H_2 becomes rich following the degradation of the NH_3 means that the degradation of NH_3 can be controlled. The reaction that produces active nitrogen is controlled by the addition of hydrogen rather than the conventional minimization of the additive amount of NH_3 , making management simple. Through the use of this method, it is possible to freely control the atmosphere in the furnace within the range producing a low K_N value, making it possible not only to form a compound layer in which the γ' -phase is the main constituent, but also to conduct nitriding with no compound layer. The next chapter will discuss the conditions for formation of the desired compound layer and the characteristics of the compound layer.

2-2. Strength of γ' -Phase

A roller pitting test was conducted under the conditions shown in Table 1 in order to evaluate the peeling resistance of the compound layer. As specified by the JIS standards, a carbon steel (S35C, specified by JIS G 4051) was used as the test material, in addition to a number of alloy steels (SNCM220, SACM645, SCr420, and SCM420, specified by JIS G 4053). The developed nitriding treatment was applied using a batch atmosphere nitriding furnace under the conditions shown in Table 2. During the application of the developed nitriding treatment, the partial pressures of the NH_3 , N_2 , and H_2 gas in the furnace were controlled as shown in Table 2, with the total pressure considered as 1. The temperature was 853K, and the treatment times were set at 5.4 ksec and 7.2 ksec, with consideration of the speed of formation of the compound layer. An infrared absorption gas analyzer was used to analyze the partial pressure of the NH_3 in the treatment environment, and a thermal conductivity gas analyzer was used to analyze the partial pressure of the H_2 .

Table 1. Test conditions for roller pitting test

Hertz contact stress	1300MPa
Small roller speed	1560rpm
Sliding ratio	-40%
Oil / Oil Temp.	ATF / 363 K

Table 2. Nitriding conditions

		Developed conditions	Conventional conditions
Partial pressure ratio	NH_3	0.16 (16.2kPa)	0.40 (40.5kPa)
	H_2	0.74 (75.0kPa)	0.28 (28.4kPa)
	N_2	0.10 (10.1kPa)	0.32 (32.4kPa)
K_N		0.25	2.70
Temperature		853 K	853 K
Nitriding time		7.2ksec	5.4ksec

Figure 4 shows the results of EBSD analysis of a compound layer produced by the developed nitriding treatment. The results show that a γ' -phase has been formed in the majority of the surface layer, there is almost no porous layer, and fine crystal grains have been formed.