

Development of Carburized High-strength Gear Steel with Less Rare Metals Added

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ABSTRACT

In conventional high-strength gear steel, the addition of Ni and Mo reduces the non-martensitic structure at the process of quenching the gear surface after carburizing. This makes the gear surface martensitic and thereby guarantees high fatigue strength. However, Ni and Mo are rare metals, and it has become impossible to ignore the increase in material costs caused by the addition of large quantities of these metals. Based on the mechanism by which non-martensitic structures form, we have developed a method for producing carburized high-strength steel in which the application of cold-oil to the quenching process improves the cooling speed and the chemical composition of the steel is optimized. Using no Ni and reducing Mo to less than half, we have developed a new gear steel with a greater level of fatigue strength than conventional steel. In other words, it was made possible to reduce the amount of rare metals used while simultaneously achieving high fatigue strength.

1. Introduction

The gears used to transmit power in a transmission use either general steel or high-strength steel depending on the performance required of them. In general, because low-speed gears, which have high-torque and frequent input, and the final gear, which is always subject to torque input, need to have high fatigue strength, there is a tendency for high-strength steel to be used for these gears. Additionally, in recent years, the need for automobiles to have reduced environmental impact and increased market appeal has led to more lightweight, compact multi-stage transmissions, and this in turn has resulted in the gears being subjected to greater loads. Typically, after a transmission gear has been forged and machined, to improve fatigue strength, carburizing and quenching are used to increase hardness, and shot peening is used to increase compressive residual stress.

Honda started using high-strength steel⁽¹⁾ in mass-production vehicles in the 1990s and is still using high-strength steel in many models today. In addition to the primary components of carbon steel, namely, C, Si, and Mn, the case-hardening steel that is used in gears that will undergo carburizing and quenching and other forms of

surface hardening treatment has Cr, Ni, Mo, V, and other alloy elements added to it in accordance with the purpose that it is being used for. While the components of the general steel known as SCr420 are C, Si, Mn, and Cr, high-strength steel has Ni and Mo added to its composition. This results in an increased rise in hardness in the outermost layer during carburizing and quenching and improved fatigue strength.

The reason carburization hardening is used to strengthen most transmission gears is that carburizing and quenching yields martensite, which is the hardest and strongest type of metal structure. Martensite can be formed by the rapid cooling of austenite. The hardness of martensite depends on the carbon concentration of the structure. The greatest hardness can be achieved at a carbon concentration between 0.7% and 0.8%⁽²⁾. The ideal state would be for the entirety of the gear from the inside to the surface to have a martensitic structure. However, this ideal state may be unachievable depending on the chemical composition of a steel and heat treatment conditions. Figure 1 shows the cross-sectional surface microstructure of gas carburized and hot-oil-quenched (a) SCr420 and (b) conventional high-strength steel. The black structure visible in the outermost layer of the SCr420 is an incompletely hardened,

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non-martensitic structure (fine pearlite structure). This structure appears because intergranular oxidation reduces the hardenability of the steel surface. Figure 2 shows the mechanism of said reduction. The phenomenon of intergranular oxidation is unique to gas carburizing. When the residual furnace oxygen or the oxygen generated by decomposition of the carburizing gas diffuses into the steel, especially at the prior austenite grain boundary near the surface, the oxygen combines with the Si, Mn, and Cr in the steel to form oxides. The austenite near the intergranular oxides has locally reduced concentration of Si, Mn, and Cr dissolved therein. This leads to a reduced hardenability⁽³⁾⁻⁽⁶⁾ and makes it difficult for martensite to be formed during quenching. Because the oxygen diffusion rate in the steel is lower than the carbon diffusion rate, the depth of intergranular oxidation is shallower than that of carburizing layer. As a result, while the gas carburized steel is high in carbon, there is a possibility that localized

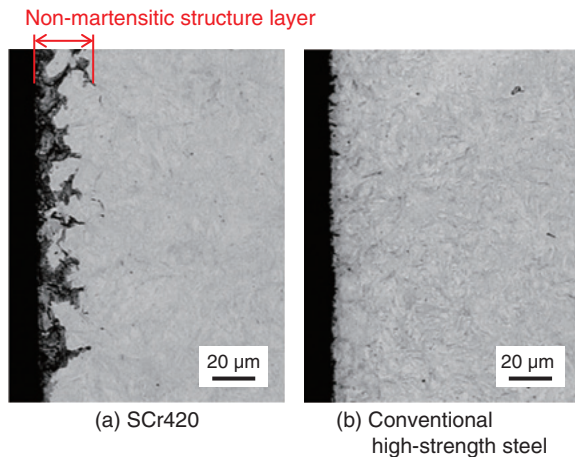


Fig. 1 Microstructure of gas-carburized steel surface

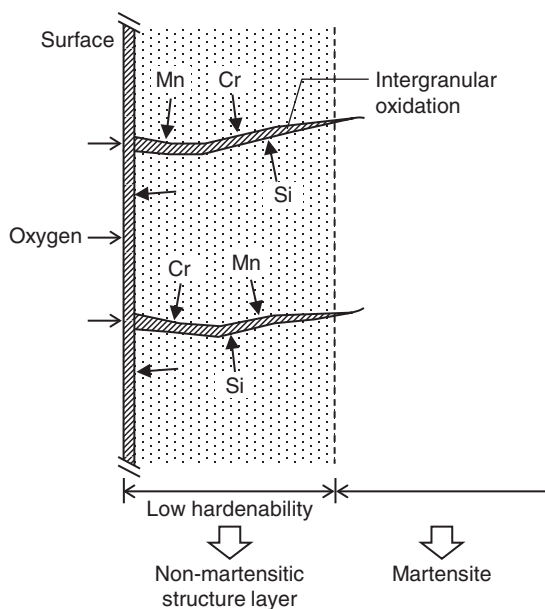


Fig. 2 Mechanism of non-martensitic structure layer generation

reduction in the hardenability in the outermost layer results in a non-martensitic structure with low hardness forming solely in the outermost layer. In conventional high-strength steel, Ni and Mo, which do not readily form oxides, are added. The addition of approximately 0.5%Ni and 0.8%Mo compensates for the reduction in the hardenability caused by the formation of intergranular oxides such as Si, Mn, and Cr. As shown in Fig. 1 (b), this results in reduced formation of non-martensitic structures and improves fatigue strength. Figure 3 shows the relationship between the depth of non-martensitic structure layer and the bending fatigue strength. The figure confirms that reducing the non-martensitic structures is an effective way of improving the fatigue strength. However, because supplies of Ni and Mo, which are rare metals, are unstable, and because these elements are subject to drastic increases in price, rising material costs have been an issue.

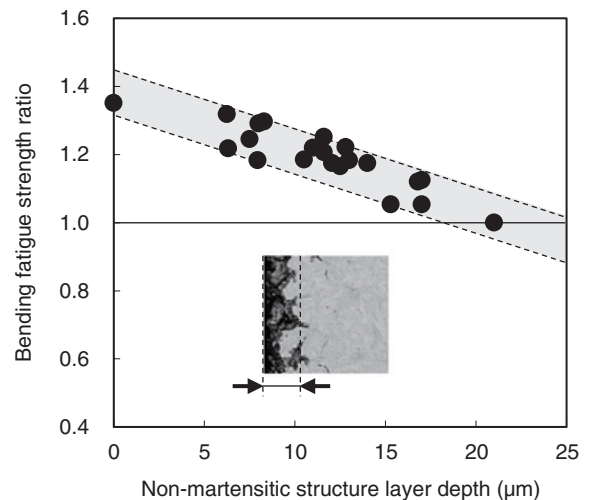


Fig. 3 Relationship between depth of non-martensitic structure layer and bending fatigue strength (SCr420 gas-carburized = 1.0)

2. Development Goals

Our goal was to reduce the cost of high-strength gear steel by a material composition design and heat treatment specifications that would make it possible to simultaneously reduce the addition of Ni and Mo and reduce the formation of non-martensitic structure (thereby increasing fatigue strength).

3. Reducing Non-martensitic Structure by Using Cold-oil Quenching

Two methods of reducing non-martensitic structure without high alloying (adding Ni and Mo) are vacuum carburizing and tooth-surface grinding after carburizing. In vacuum carburizing, there is no oxygen in the furnace, and intergranular oxidation does not occur. This means that there

is no reduction in the hardenability in the steel surface, and there is generally no non-martensitic structure. However, gas carburizing is currently dominant at Honda and other related manufacturers, and given existing facilities, the widespread application of vacuum carburization would be difficult. In tooth-surface grinding after carburizing, even if non-martensitic structure is formed, it can be ground away. However, in normal tooth-surface grinding, only the tooth flank surfaces are ground. This means that non-martensitic structures remain at the root of the teeth, and the tooth bending fatigue strength cannot be improved. Additionally, presupposing the use of tooth-surface grinding will lead to increased part costs. For the above reasons, it was decided to focus on developing a method using cold-oil quenching, which can be implemented using existing facilities and can reduce the formation of non-martensitic structure over the entire gear surface.

Typically, a gear is carburized at approximately 930°C and then cooled to 850°C. This temperature is held, and then the gear is rapidly cooled through oil quenching. At this time, whether non-martensitic structure forms on the steel surface depends on the hardenability of the material and the cooling rate during quenching. Figure 4 is a schematic diagram of the continuous cooling transformation (CCT) curve. When the cooling curve passes the pearlite transformation start line (line Ps), fine pearlite structures form. Figure 4 corresponds to the state of the surface of the gas-carburized SCr420 discussed in chapter 1. On the other hand, if the cooling curve does not pass line Ps, non-martensitic structure will not form. In other words, to reduce the formation of non-martensitic structure, it is necessary to help prevent the cooling curve from passing line Ps by shifting line Ps to the right along the time axis, shifting the cooling curve to the left along the time axis, or doing both. Mn, Cr, Ni, Mo, etc. are elements that have the effect of shifting line Ps to the right along the time axis. Among those elements, Ni and Mo, which have low affinities for oxygen and low susceptibility to intergranular oxidation, have been used for a hardening method for conventional high-strength steel.

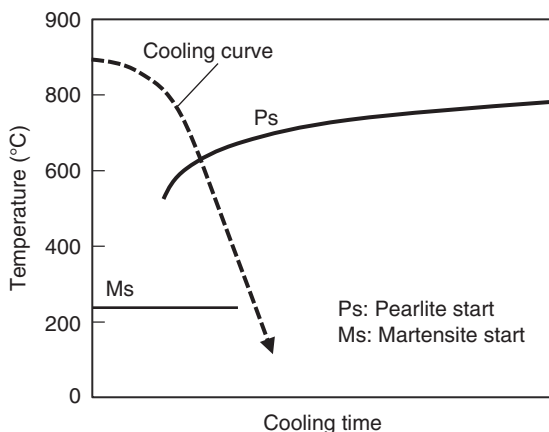


Fig. 4 Schematic diagram of CCT curve

In the developed method, to reduce the addition of Ni and Mo, cold-oil quenching was used as a means of moving the cooling curve to the left along the time axis; that is, increasing the cooling rate. Typically, cold-quenching oil is used to ensure the internal hardness of the large gears used in construction equipment and other parts with high heat masses. However, in the developed method, we cooperated with an oil manufacturer to select a cold-quenching oil that excels in cooling the outermost surface of steel. Figure 5 shows the cooling curves of some of the cold-quenching oils that were considered, which are labeled as cold-quenching oils (A), (B), and (C)⁽⁷⁾. The figure also shows the cooling curve of one of the hot-quenching oils used in mass production. Figure 6 shows the measured Barkhausen noise (BN)⁽⁸⁾ values of the outermost root surfaces of the gear carburized and quenched by cold oils (A), (B), and (C). The BN value correlates with the microstructure and hardness of the steel, and a smaller BN value corresponds to a higher hardness. Therefore, cold-quenching oil (C) was selected as the cold-quenching oil that most reliably increases the hardness of the outermost gear root surfaces.

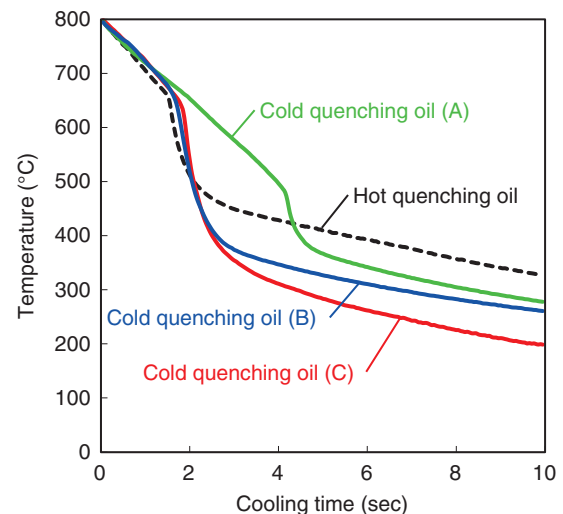


Fig. 5 Cooling characteristics of quenching oil (JIS-K-2242 method, silver probe test)

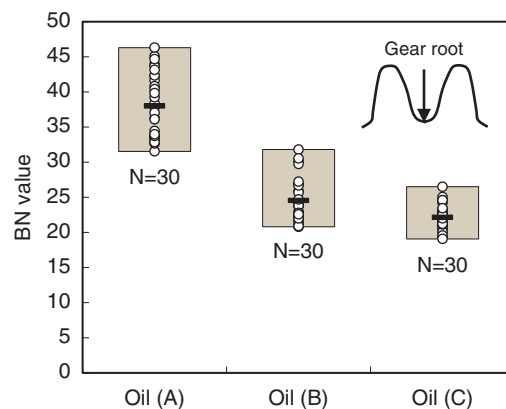


Fig. 6 Barkhausen noise (BN) value of gear root quenched by cold oil (A), (B), (C)

4. Material Composition Design

Presupposing the gas carburizing and quenching using the cold-quenching oil selected in chapter 3, a component balance that would be effective for reducing the formation of non-martensitic structure was searched. First, we calculated the perlite transformation start line of the SCr420 carburized surface by using Sente software Ltd.'s JMatPro simulation software. In this calculation, we set the carbon concentration on the surface of SCr420 as 0.75% to simulate a carburized surface. In Fig. 7, both Ps_1 and Ps_2 were the calculated results. Ps_1 stands for the perlite transformation start line with no intergranular oxidation, and Ps_2 stands for the same line in consideration of concentration reduction of dissolved Si, Mn, and Cr accompanying intergranular oxidation. In the figure, temperature hysteresis when gear surface temperatures were measured in the cold-oil quenching from 850°C is indicated as a cooling curve. Compared to Ps_1 , Ps_2 is shifted to the left on the time axis and intersects with the cooling curve. This means that even if the selected cold-quenching oil is used, in compositions, such as SCr420, in which components with low affinity for oxygen, such as Ni and Mo, are not added, intergranular oxidation will lead to localized insufficiencies in the hardenability, and non-martensitic structure may form. Thus, in our steel development, we focused on Mo because it has higher hardenability than Ni though used in smaller amounts. Optimal amount of added Mo was sought. In Fig. 7, Ps_3 shows the calculated result of the developed steel (with 0.3% Mo added). As in Ps_2 , it is simulated that the steel surface during carburizing with a 0.75% carbon concentration and intergranular oxidation is also taken into account. Ps_3 does not intersect with the cooling curve, and this indicates that it is possible to suppress the formation of non-martensitic structure through adding no Ni and reducing Mo to less than half compared to conventional high-strength steel.

Ways to reduce the depth of intergranular oxidation were sought. Figure 8 shows the effects of Si, Mn, and Cr on intergranular oxidation depth. It was found that to reduce

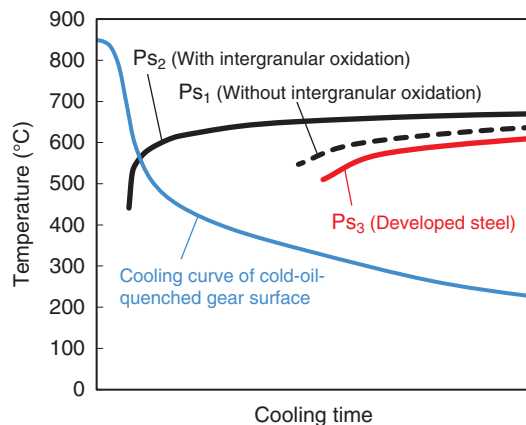


Fig. 7 CCT curve of SCr420 (0% Ni, 0% Mo) and developed steel (0% Ni, 0.3% Mo)

Table 1 Chemical composition

	(mass%)					
	C	Si	Mn	Ni	Cr	Mo
Developed Steel	0.20	0.08	0.65	-	1.05	0.35
Conventional high-strength steel	0.20	0.05	0.40	0.50	0.60	0.80

the intergranular oxidation depth, in addition to reducing the amount of Si added, increasing the ratio of Cr to Mn is also effective. The depth of the intergranular oxidation of conventional high-strength steel is approximately 5 μm . To achieve a similar grain boundary oxidation depth, the amount of Si added was reduced and a composition that satisfies the condition $\text{Cr/Mn} \geq 1.3$ was used.

On the basis of the above results, composition of the developed steel was determined. Table 1 shows a representative composition of the developed steel. Figure 9 shows the cross-sectional surface microstructures of SCr420 and developed steel that are gas carburized and cold-oil quenched. In the SCr420, non-martensitic structure

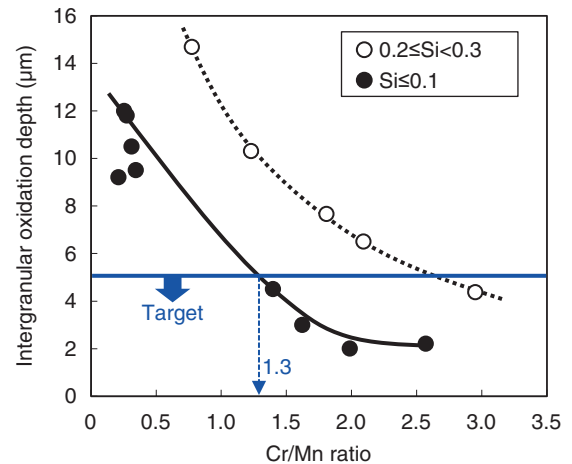


Fig. 8 Relationship between Cr/Mn ratio and intergranular oxidation depth

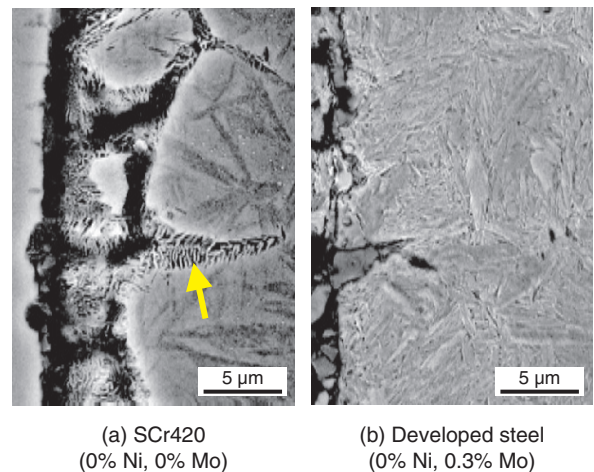


Fig. 9 Scanning electron micrograph of steel surface that was gas-carburized and cold-oil quenched (Arrow mark indicates non-martensitic structure)

can be identified near the intergranular oxidation. However, suppression of these structures was confirmed in the developed steel.

5. Characteristics of Developed Steel

5.1. Heat Treatment Quality

Figure 10 provides an example of the microstructure and hardness distribution of the developed steel after gas-carburizing and quenching and tempering. Just as in the conventional high-strength steel shown in Fig. 1 (b), the developed steel has a structure in which the formation of non-martensitic structure is reduced and also has a high surface hardness (of 720 HV or greater).

5.2. Gear Fatigue Strength

To compare the gear fatigue strengths of the developed steel and conventional high-strength steel, the tooth bending fatigue strength and the pitting strength were evaluated by using a gear fatigue testing machine. The gears used for the evaluation of both types of steel had the same shape, and no tooth-surface grinding was performed after carburization. Figure 11 shows the results of the gear fatigue testing. In

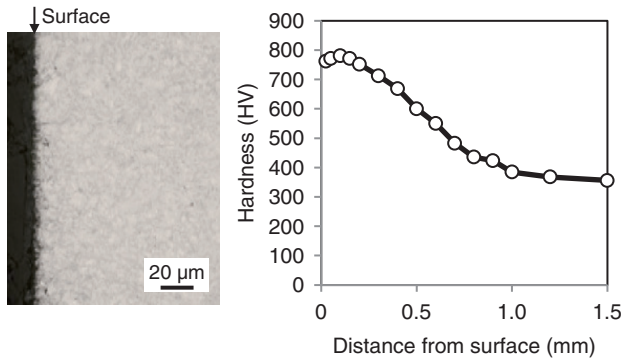


Fig. 10 Microstructure and hardness distribution of gas-carburized developed steel

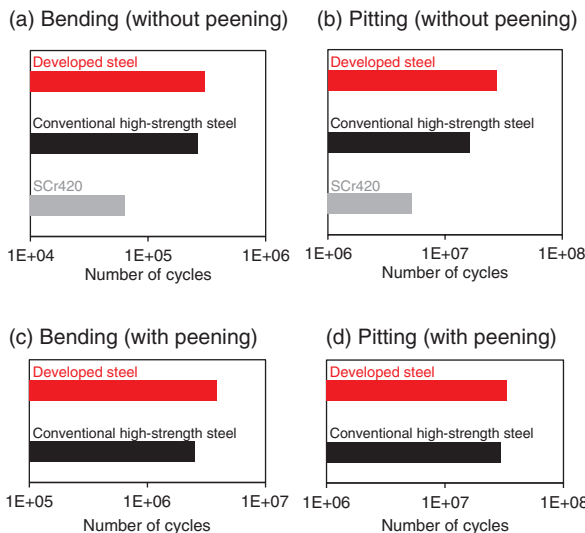


Fig. 11 Gear bending and pitting fatigue strength

the tooth bending, a test torque of 320 Nm was used, and in the pitting, a test torque of 200 Nm was used. Results (a) and (b) are for when there is no peening after carburization. Results (c) and (d) are for when there is peening after carburization. In all the results, the developed steel exhibits a fatigue strength that is equivalent to or greater than that of conventional high-strength steel. Figure 12 shows the strength position of the developed steel.

5.3. Tooth Precision

To compare the heat-treatment distortion characteristics of the developed steel and conventional high-strength steel, we evaluated the dimensional variation after heat treatment by using a final gear that is a representative example of high-strength steel parts. The final gear made of the developed steel was produced with the same processes as mass production except for carburizing and quenching processes. As one of the evaluation results, Fig. 13 shows lead slope deviation. Both the dimensional variation and its deviation of the developed steel were confirmed to be equivalent to or less than those of conventional high-strength steel.

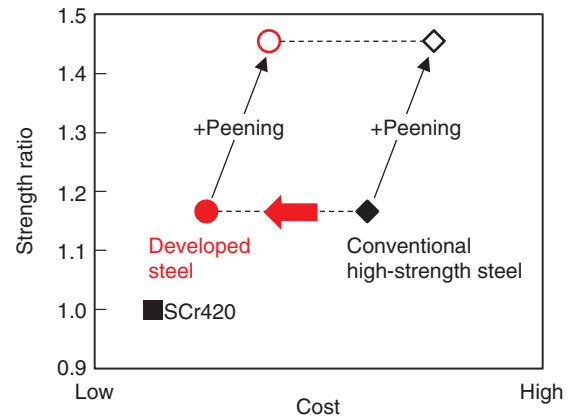


Fig. 12 Position of developed steel

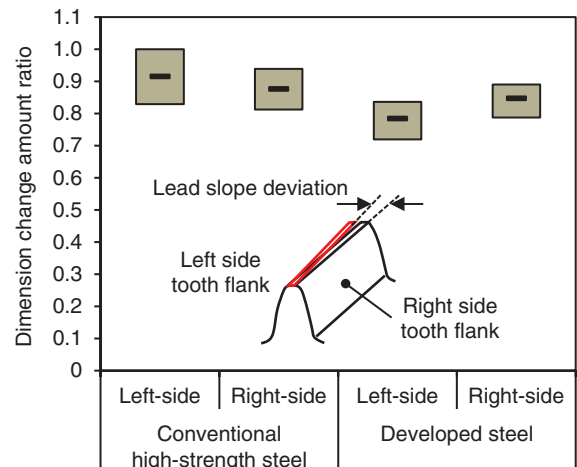


Fig. 13 Dimension (Lead slope deviation) change amount (Maximum change amount = 1.0)

6. Conclusion

By designing the optimal steel composition for carburizing and cold-oil quenching, a high-strength gear steel of equivalent or greater strength than conventional high-strength steel was developed, with lower amounts added of the rare metals Ni and Mo. Thus, cost reduction was achieved by using the developed steel instead of conventional high-strength steel. The following facts have been made clear in the course of development.

- (1) It is possible to reduce the formation of non-martensitic structure while mitigating increases in material costs by appropriately combining increased cooling rate during quenching and material composition design.
- (2) Cold-oil quenching eliminates the need for Ni and reduces the amount of Mo to less than half, which were necessary for conventional, hot-oil quenched high-strength steel.
- (3) To decrease the intergranular oxidation depth, which is one cause of non-martensitic structure formation in gas carburizing and quenching, in addition to reducing the amount of Si added, increasing the ratio of Cr to Mn is also effective.

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