# Influence of Ti Precipitate in Carburizing Steel Containing Boron

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*When cold forged gear steel is carburized, fine precipitates of TiC prevent austenite grain from coarsening. While preventing grain from coarsening, these precipitates increase the deformation resistance against cold forging due to precipitation hardening. This study evaluates the influence of TiC precipitates on the deformation resistance, as well as their characteristics that work to prevent grain coarsening during the carburization of a steel containing boron.*

## Introduction

Cold forging has caught the attention of automobile manufacturers in recent years because the process emits less $CO_2$ and enables lower-cost production than conventional forming methods such as cutting and hot forging. In particular, there is an increasing need for the steel used to produce cold-forged gears. Cold forging of steel, however, is associated with a deformation resistance much higher than that associated with hot-forging. Because of this, it is difficult to form complex shaped parts, such as gears, by cold forging. Thus steel for cold forged gears is required to have a deformation resistance much lower than that of conventional gear steel.

On the other hand, gears are carburized for strengthening. If the gears are cold forged before carburizing, the strain energy induced by the cold forging can cause crystal grain to coarsen during carburization, which may adversely affect the accuracy of the parts. To prevent this, steel for cold forged gears contains alloying elements, such as Al, Nb and Ti, which precipitate carbonitrides having a "pinning effect". This pinning effect has long been exploited to prevent crystal grain from coarsening. The addition of these elements, however, increases the deformation resistance. Thus, it is important to exert the pinning effect effectively by carefully controlling the precipitation state of the carbonitrides while minimizing the amount of alloying elements added.

With this background, a study was conducted on the effect of the precipitation state of carbonitrides, as reported in this paper. This study aims to develop a steel that has a small deformation resistance, is effective in preventing crystal grain from coarsening and is suitable for the cold forging of gears.

## 1. Considerations on steel for cold forged gears

Steel for cold forged gears exploits the pinning effect exerted by carbonitrides of elements such as Al, Nb and Ti to prevent the coarsening of crystal grains. To effectively exert this pinning effect, it is necessary to secure a large number density of carbonitride precipitates during carburization by suppressing Ostwald ripening, in which large precipitates grow larger by absorbing adjacent smaller precipitates. Since Ostwald ripening is a phenomenon accompanying atomic diffusion, alloying elements with low diffusion coefficients are preferable for effectively exerting the pinning effect[1]. The diffusion coefficients of Al, Nb and Ti (**Table 1**) indicate that Ti is the most effective element in exerting the pinning effect.

As shown in **Fig. 1**[2], the pinning effect can be explained by a force acting to grow crystal grains (hereinafter referred to as "growth force") and a force exerted by precipitates and acting to suppress grain growth (hereinafter referred to as "suppressive force"). The growth force is given by Formula (1) according to the Gibbs-Thomson law:

**Table 1** Diffusion coefficient forming carbonitride

| Element | Diffusion coefficient ($m^2$/sec) | Precipitation |
|---|---|---|
| Al | $3.0\times10^{-3}$ | AlN |
| Nb | $5.6\times10^{-4}$ | NbCN |
| Ti | $1.5\times10^{-5}$ | TiC |

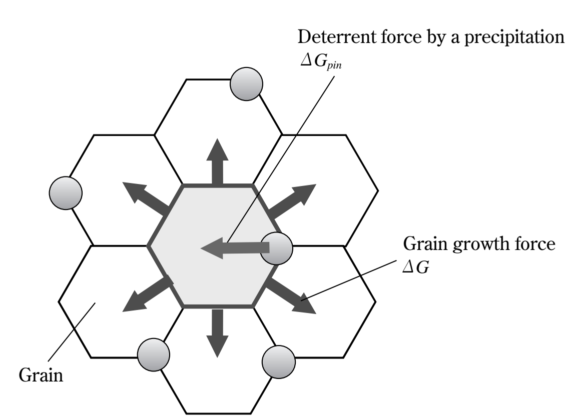


**Fig. 1** Schema of grain growth and pinning effect

$$\Delta G \approx \frac{4\sigma V}{D} \quad \cdots\cdots(1)$$

wherein $\Delta G$ : growth force

$\sigma$ : grain boundary energy

$V$ : molar volume

$D$ : crystal grain diameter

On the other hand, the suppressive force is given by Formula (2) according to the Zener-Smith model:

$$\Delta G_{pin} \approx \frac{\pi d \sigma}{2} nV \quad \cdots\cdots(2)$$

wherein $\Delta G_{pin}$ : suppressive force

$d$ : diameter of precipitates

$n$ : number density of precipitates per unit area

In the case where grain boundary growth is suppressed, the growth force and suppressive force become equal ($\Delta G = \Delta G_{pin}$:), and thus the relationship between the grain diameter and precipitates diameter is given by Formula (3).

$$D \approx \frac{8}{\pi n d} \quad \cdots\cdots(3)$$

Formula (3) indicates that grain coarsening is more effectively suppressed by precipitates grown in a high number density and having large diameters.

On the other hand, the precipitates generated may trigger the precipitation strengthening mechanism, increasing the deformation resistance during cold forging. The precipitation strengthening is given by Formula (4) according to the Ashby-Orowan model[3]:

$$\Delta \sigma = 2.95\sqrt{\pi n} \ln\left(\frac{d}{2.5\times10^{-4}}\right) \quad \cdots\cdots(4)$$

where $\Delta \sigma$ is the deformation resistance increment.

Formula (4) indicates that the deformation resistance during cold forging increases with higher precipitate density and larger precipitate diameter. In other words, properly controlling the precipitate density and grain size can suppress grain coarsening during carburizing and prevents the deformation resistance from increasing during cold forging.

## 2. Experimental method

Two types of steel, as shown in **Table 2**, were used for the present experiment, i.e., carburizing steel containing Ti and B, and SCM420H, which is generally used for gears. In order to clarify the effect of precipitation states on the deformation resistance and on the characteristic of preventing grain from coarsening, the carburizing steel containing Ti and B was subjected to four kinds of heat treatment (i.e., conditions ① to ④) to prepare steel samples having different precipitation states of TiC, as shown in **Fig. 2** and **Fig. 3**.

To study the deformation resistance, all the steel samples (the carburizing steel containing Ti and B, heat-treated under conditions ① to ④, plus SCM420H) were formed into solid cylinders, each having a dimension of $\phi 20 \times 30$mm. The cylindrical specimens were compressed with their ends confined with a compression rate of 75%. After this compression test, the specimens were carburized at 950℃ to investigate the characteristic of preventing grain from coarsening. Observations to determine grain size number were conducted in the area including an equivalent strain of 2.0, as shown in **Fig. 4** (the area surrounded by a broken line in the figure).

Table 2 Chemical composition of specimens

| Steel | Chemical composition (mass%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | C | Si | Mn | Cr | Mo | Ti | B |
| Carburizingsteel containg B | 0.17 | 0.06 | 0.44 | 1.38 | — | 0.04 | add |
| SCM420H | 0.20 | 0.18 | 0.83 | 1.12 | 0.17 | — | — |

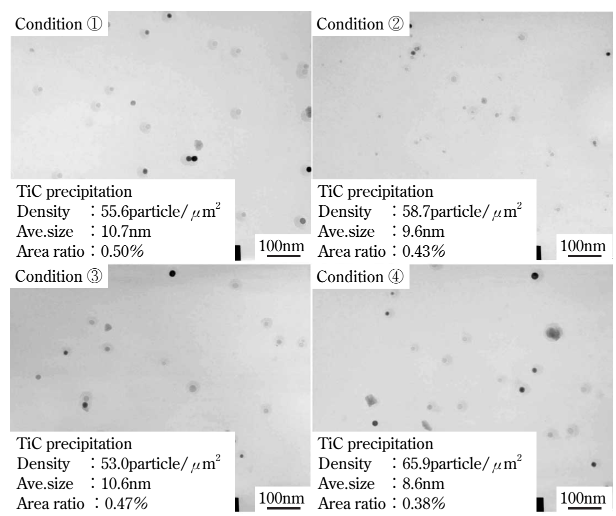


Fig. 2 Precipitation condition of TiC

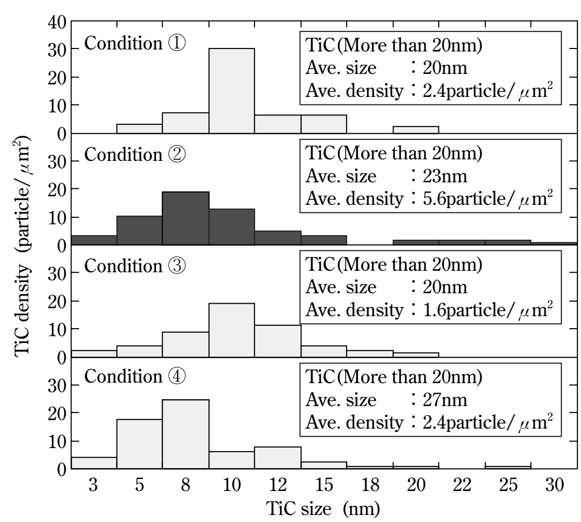


Fig. 3 Condition of TiC distribution

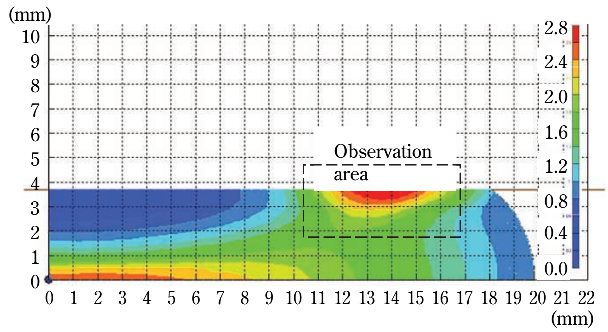


Fig. 4 Position of investigation for size of grains

## 3. Experimental results

**Fig. 5** shows the deformation resistance of materials softened under conditions ① to ④. Almost no difference was found in the deformation resistance for carburizing steels containing Ti and B, treated under conditions ① to ④. (Their hardness is about 16% lower than that of SCM420H.) The results indicate that the difference in the precipitation state of TiC, investigated in this experiment, does not significantly affect the deformation resistance.

**Fig. 6** depicts micrographs showing the grain size numbers of specimens carburized after a compression test. These micrographs indicate that the grain size numbers of the top-most surface layers all fall around No.12 regardless of which of the ① to ④ conditions applies; they show no difference. It should be noted however that, at a depth deeper than 400 $\mu$m from the surface layer, conditions ①, ③ and ④ (unlike condition ②) yielded coarser grains with grain size numbers no greater than No. 3, as observed in the area surrounded by circles in the figures. This is despite the fact that conditions ① to ④ all yield an average grain size number of around No.8.

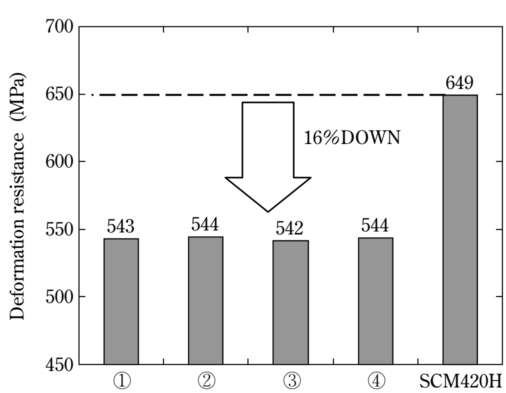


Fig. 5 Deformation resistance of each specimen

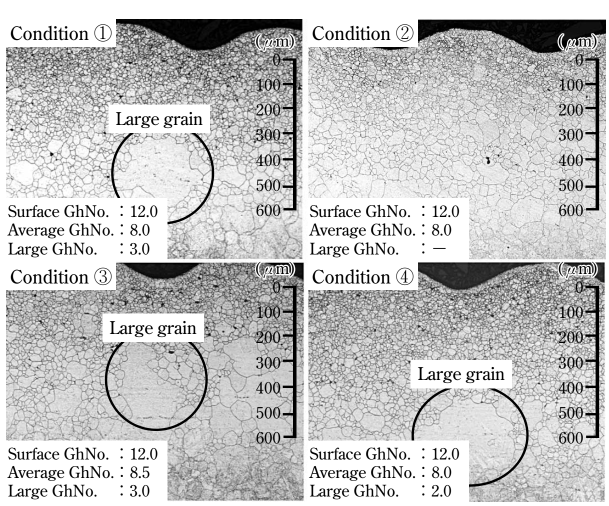


Fig. 6 Grain size of carburized specimen after compressing test

## 4. Discussions

### 4.1 Effect of precipitation state on deformation resistance

Formula (4) indicates that the deformation resistance during cold forging is affected by the grain size and density of precipitates. The materials, treated under conditions ① to ④, have precipitates (TiC) with different diameters and densities, as shown in Fig. 2 and Fig. 3; however, they resulted in almost no significant difference, with their deformation resistances falling around 542 to 544MPa, as shown in Fig. 5. The effect of the precipitation state on deformation resistance is calculated by applying the values of the density and average size, shown in Fig. 2, to Formula (4). As shown in **Table 3**, the increments in deformation resistance for the precipitation state of conditions ① to ④ are calculated to be 143 to 150MPa, showing hardly any difference, just as in the case of the measured values. Therefore, the precipitates from conditions ① to ④ are regarded as having almost no effect on the deformation resistance.

### 4.2 TiC effect of preventing crystal grain coarsening

As shown in Fig. 6, all the conditions, ① to ④, resulted in surfaces with a grain size number of No.12 (grain size: about 6 $\mu$m), with hardly any differences. These fine crystal grains are attributable to the pinning effect of TiC. According to Formula (3), grain size can be evaluated by precipitate diameter and density. Assuming that TiC, observed before carburization, remains unchanged after carburizing, Formula (3) yields grain sizes of 4.3 to 4.5 $\mu$m for conditions ① to ④, using the values shown in Fig. 2. These values agree with the observed values, showing hardly any differences. These results indicate that the majority of TiC precipitates effectively exert a pinning effect.

On the other hand, for conditions ①, ③ and ④, coarse crystal grains with a grain number of 8 (grain size: about 22 $\mu$m), were observed at a depth deeper than 400 $\mu$m (Fig. 6). These coarse grains are attributable to the less effective pinning effect exerted by smaller TiC precipitates, which are energetically less stable than larger ones, and dissolve into the solid matrix during carburization, decreasing the number density of the precipitates.

The solid solubility of these precipitates can generally be explained by solubility curves such as the one shown in **Fig. 7**[4]. In Fig. 7, dissolved Ti becomes more stable as the concentrations of Ti and C approach the lower left corner, and TiC becomes more stable as the concentrations approach the upper right corner, with respect to the border curve for the carburizing temperature of 950℃. Thus it is considered that the carburized steel containing B has a lower C concentration in its interior than in its surface layer, making TiC less stable. It is also considered that, in the interior of the carburizing steel containing B, smaller TiC precipitates, which are energetically less stable, dissolve into the solid matrix, leaving relatively larger TiC precipitates in the matrix during carburization. Thus, it is possible to quantitatively evaluate the crystal grain coarsening from the condition of the relatively larger TiC precipitates observed before carburization. Assuming that the TiC precipitates larger than 20nm, as shown in Fig. 3, remain effective in exerting a pinning effect during carburization without being dissolved into the matrix to form a solid solution, Formula (3), provided with their average diameter and number density, yields grain sizes for conditions ① to ④, as shown in **Fig. 8**. Fig. 8 indicates that condition ②, which caused no crystal grain coarsening yielded a measured grain size that agrees well with the calculated value. On the other hand, conditions ①, ③ and ④, which caused crystal grain coarsening, resulted in calculated values greater than 40 $\mu$m (grain number, No.6). These results consistently elucidate the fact that, at a depth deeper than 400 $\mu$m from the surface, TiC precipitates smaller than 20nm dissolve into the matrix to form a solid solution during carburization, losing their pinning effect and leaving only TiC greater than 20nm exerting the pinning effect.

From the above, the behaviors of TiC and crystal grains, during carburization in the B-containing carburizing steel, are classified into two cases as shown in **Fig. 9**, i.e., Case I, where a small number of TiC precipitates greater than 20nm exist; and Case II, where a large number of TiC precipitates greater than 20nm exist. In Case I, the surface layer has a C concentration high enough to maintain TiC

**Table 3** Deformation resistance and calculation of the influence by precipitation hardening

| Heat history | Measurement (MPa) | Calculation (MPa) |
|---|---|---|
| | Deformation resistance | Increase of deformation by precipitation |
| Condition ① | 543 | 146 |
| Condition ② | 544 | 146 |
| Condition ③ | 542 | 143 |
| Condition ④ | 544 | 150 |

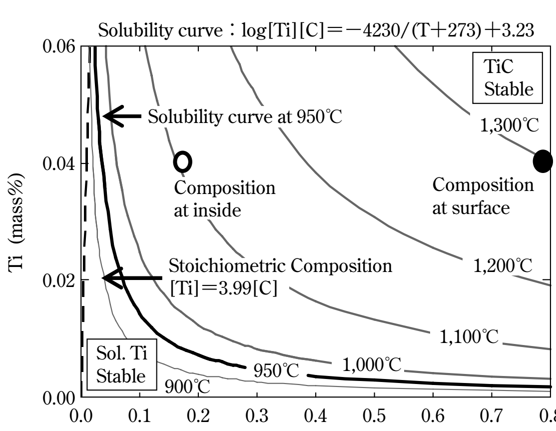


**Fig. 7** Solubility Curve of TiC

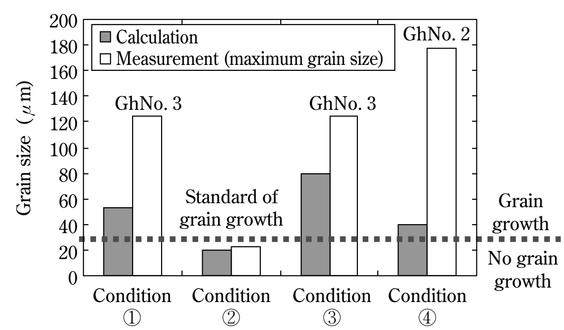


**Fig. 8** Comparison of measurement value and calculation in grain size around 400 $\mu$m from surface

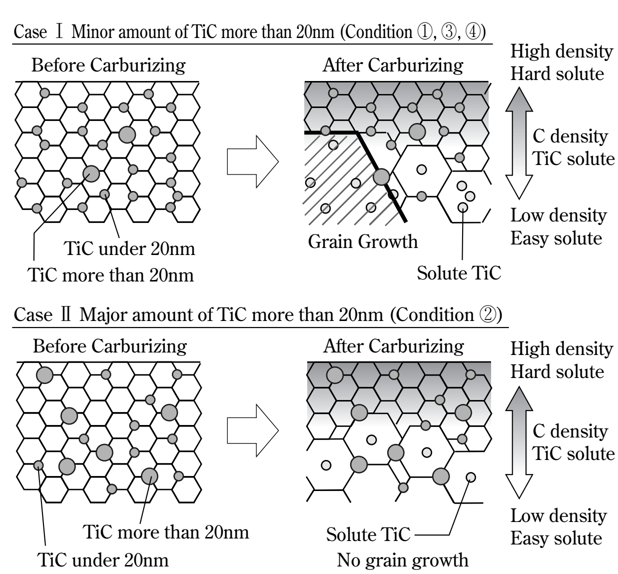


**Fig. 9** Schema of relation of TiC and grain size by carburization

precipitates stably regardless of their sizes, which prevents the crystal grain from coarsening. Meanwhile, in the interior, the C concentration becomes low, causing TiC precipitates smaller than 20nm to dissolve into the matrix to form a solid solution, which decreases the number of particles contributing to the pinning and causes crystal grain coarsening. On the other hand, in Case Ⅱ, the surface layer has a C concentration high enough to maintain TiC precipitates stably regardless of their sizes, which prevents crystal grain coarsening; this is the same as in Case I. However, in the interior, C concentration becomes so low that TiC precipitates smaller than 20nm dissolve into the matrix to form a solid solution. Meanwhile, TiC precipitates larger than 20nm remain undissolved, ensuring the number of particles contributing to the pinning, which serves to prevent crystal grain coarsening.

**Conclusions**

A study was conducted with the aim of developing a steel for cold forged gears that has decreased deformation resistance and the effect of preventing crystal grain coarsening. The following results were obtained:

(1) Conditions ① to ④, applied for varying precipitation states without changing the composition, resulted in no significant difference in the deformation resistance.
(2) Conditions ① to ④ yielded different grain size distributions after carburization following compression. Crystal grain coarsening was prevented effectively in the surface layer under all of the conditions; however, only condition ② was effective in preventing the grain from coarsening at a depth of around 400$\mu$m from the surface layer.
(3) For conditions ①, ③ and ④, grain coarsening occurred at a depth of about 400$\mu$m from the surface. This is attributable to the lower density of TiC precipitates larger than 20nm, compared with the case of condition ②.

## References

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