

# Development of Carburizing Steel for Innovation in Parts Manufacturing Process

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## ABSTRACT

In order to develop a new carburizing steel material that realizes an intermediate heat treatment-free process in parts manufacturing, the cold forgeability of the as-rolled steel and suppression of abnormal grain growth of austenite were studied. It was shown that adjustment of addition amount of Si, Mn and Cr, suppression of dynamic strain aging during cold forging, and an increase of ferrite fraction by controlled rolling contribute to the reduction of deformation resistance. However, Nb precipitation control by fully utilizing mill manufacturing processes was also necessary for suppression of abnormal grain growth of austenite. A new steel for carburizing was developed by integrating these technologies, making it possible to eliminate annealing before cold forging and normalizing before carburizing simultaneously. Thus, the developed steel is an important innovation in the parts manufacturing process.

**CITATION:** Imanami, Y., Tomita, K., Fukuoka, K., and Nishimura, K., "Development of Carburizing Steel for Innovation in Parts Manufacturing Process," *SAE Int. J. Engines* 10(2):2017, doi:10.4271/2017-01-0378.

## INTRODUCTION

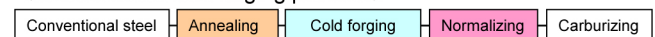
Machine parts such as automotive gears have complicated shapes, and many are forged in the hot or cold state. Carburizing heat treatment is performed after forging in order to improve fatigue strength. Cold forging is excellent in dimensional accuracy, enabling near net shape forming. For this reason, a change from hot forging to cold forging makes it possible to improve the available percentage by reducing the cutting amount after forging. An example of the manufacturing process of cold forging parts is shown in Figure 1. In cold forging, annealing is commonly performed to reduce deformation resistance, and normalizing before carburizing has also been used to suppress coarsening of austenite grains during carburizing. However, due to intensified parts price competition in recent years, development of steel that can reduce parts manufacturing costs, for example, by omitting the intermediate processes of annealing and normalizing, has become important. In order to develop a new steel which makes it possible to eliminate intermediate heat treatments in the cold forging process, the cold forgeability of steel and abnormal grain growth of austenite were investigated. The comparable product is SCM420 as the volume zone steel for carburizing.

## MATERIAL DEVELOPMENT TO IMPROVE COLD FORGEABILITY

Deformation resistance and forming limit are considered as important factors in cold forgeability. In general, reduction of static strength such as hardness and tensile strength is effective for reducing deformation resistance<sup>1)</sup>. However, because cold forging causes a temperature increase due to plastic deformation, it is also necessary to consider dynamic strain aging<sup>2,3)</sup>. Steel for carburizing, as

represented by SCM420 in the JIS standard, has high hardenability. After hot rolling and cooling, the microstructure becomes ferrite and pearlite containing bainite. Since bainite is the hardest of these microstructures, preventing formation of bainite is effective for reducing deformation resistance. On the other hand, ferrite is the softest of these microstructures. Thus, in order to reduce deformation resistance, the ideal approach is to increase the ferrite fraction. The effect of hot rolling conditions on the as-rolled microstructure was investigated with the aim of obtaining the ideal microstructure.

### <Conventional cold forging process>



### <Target process>

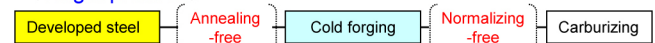


Figure 1. Conventional process and target process.

Si, Mn and Cr in steel influence hardness after hot rolling through their effects on the solid solution strengthening of ferrite<sup>4)</sup> and lamellar spacing of pearlite<sup>5)</sup>. These elements also strongly influence hardenability. Therefore, their influences on hardness after hot rolling and hardenability were investigated in order to achieve both low hardness on the same level as annealed SCM420 and comparable hardenability to SCM420.

As a result of the temperature increase caused by plastic deformation during cold forging, dynamic strain aging due to solid solution N is considered to increase work hardening<sup>6)</sup>. Therefore, suppression of dynamic strain aging by fixing solid solution N was investigated.

After hot rolling, the developed steel exhibits a ferrite and pearlite structure, as described above. However, annealed SCM420 has a ferrite and spheroidized cementite microstructure. The effect of this difference in the microstructure on forming limit was investigated.

## MATERIAL DEVELOPMENT TO SUPPRESS ABNORMAL GRAIN GROWTH OF AUSTENITE

If prior austenite undergoes abnormal grain growth, the fatigue strength of steel has been reported to deteriorate compared to the case of no abnormal grain growth<sup>7)</sup>. In carburizing after cold forging, abnormal grain growth is promoted by the effect of strain induced by cold forging<sup>8)</sup>. For this reason, additional normalizing before carburizing in order to suppress abnormal grain growth has been unavoidable with steels such as SCM420. In general, grain boundary pinning by fine dispersion of precipitates is effective to suppress abnormal grain growth. Carbonitride former elements such as Nb, Ti and V are mainly used to form such fine precipitates<sup>9-10-11-12-13-14-15-16-17-18-19-20-21-22-23)</sup>. However, Ti has a risk of forming coarse TiN, which decreases fatigue strength by increasing fatigue initiation sites<sup>24)</sup>, and V precipitates do not have a sufficient pinning force due to their dissolution at the carburizing temperature. Therefore, steel containing only added Nb was used in this development, and the optimal precipitation control method was studied.

Both increasing the amount of precipitates and reducing the size of the precipitates are important for improving the grain boundary pinning force<sup>25)</sup>. In the thermodynamic equilibrium state, the relationship between temperature and the amount of precipitation can be calculated from the solubility product of the precipitates. For example, Figure 2 shows the relationship between temperature and precipitation amount in the case of NbC. As the temperature increases, precipitation amount of NbC decreases. On the other hand, as the amount of Nb addition increases, NbC precipitation amount also increases. Here, the intersection of the NbC precipitation curve and the x-axis shows the complete dissolution temperature of NbC. This temperature becomes higher as the amount of Nb addition increases. Assuming an actual hot rolling process, Figure 3 shows an ideal precipitation control method constructed based on the above-mentioned NbC precipitation curve. Coarse Nb precipitates exist in as-cast blooms obtained by continuous casting. If these coarse Nb precipitates remain until carburizing, precipitation of fine NbC decreases, resulting in a shortage of pinning force. That is to say, coarse Nb precipitates should not remain until carburizing. Thus, it is important to dissolve coarse Nb precipitates during hot rolling by increasing the hot rolling temperature to above the complete dissolution temperature of NbC. Although addition of Nb to steel increases the amount of NbC precipitation, the complete dissolution temperature of NbC also increases with Nb addition. For this reason, Nb addition should be limited to a level at which the complete dissolution temperature of NbC does not exceed the heating temperature limit of the furnace.

## EXPERIMENTAL PROCEDURE FOR COLD FORGEABILITY

Table 1 shows the chemical compositions of the tested steels. With Steel A, hot working was done with a Thermecmastor manufactured by Fuji Electronic Industrial Co., Ltd. to investigate the influence of the hot rolling temperature on the as-rolled microstructure. After hot working, Steel A was etched with 3% nital to observe the microstructure by optical microscopy.

Table 1. Chemical compositions of steels.

| Steel  | (Mass%) |        |        |        |     |        |      |
|--------|---------|--------|--------|--------|-----|--------|------|
|        | C       | Si     | Mn     | Cr     | Mo  | Nb     | N    |
| SCM420 | 0.2     | 0.2    | 0.8    | 1.1    | 0.2 | -      | 0.01 |
| A      | 0.2     | 0.2    | 0.8    | 1.1    | -   | -      | 0.01 |
| B-G    | 0.2     | Varies | Varies | Varies | -   | -      | 0.01 |
| H      | 0.2     | 0.2    | 0.8    | 1.1    | -   | -      | 0.01 |
| I      | 0.2     | 0.2    | 0.8    | 1.1    | -   | -      | Tr.  |
| J-L    | 0.2     | 0.2    | 0.8    | 1.1    | -   | Varies | Tr.  |

To investigate the effects of Si, Mn and Cr contents on hardness after hot rolling, Steels B to G with different Si, Mn and Cr contents were melted. These steels were heated to 1473K to perform extend forging. The forged round bars were then cooled to room temperature, and their Vickers hardness was measured. The influence of Si, Mn and Cr contents on the hardenability was examined using the  $\beta$  value proposed by Ueno et al<sup>26)</sup>. Here, the  $\beta$  value is a so-called Mn equivalent value, which is expressed by the following equation (1). The coefficient value of this equation indicates the degree of influence on the hardenability. The  $\beta$  value is a parameter obtained by the Jominy test.

$$\beta(\%) = 2.7C + 0.4Si + Mn + 0.45Ni + 0.8Cr + Mo \quad (1)$$

To investigate the effect of solute N on dynamic strain aging during cold forging, N solid solution steel (Steel H) and N fixed steel (Steel I) were melted. In the N fixed steel, N was reduced in vacuum melting. In addition, a nitride forming element was added. These samples were cooled to room temperature after hot rolling, and tensile tests were carried out at the strain rate of  $1s^{-1}$  and temperature of 473K to simulate the temperature increase due to plastic deformation during cold forging.

After completion of the alloy design, the cold forgeability of actually-manufactured samples of the developed steel was evaluated by deformation resistance and forming limit. Measurement of deformation resistance conformed to the cold upsetting test method<sup>27)</sup>. That is, deformation resistance was calculated from the load at the upsetting ratio of 60% by using a cylindrical test piece with dimensions of  $\phi 15 \times 22.5mm$ . Forming limit was measured with a cylindrical test piece having dimensions of  $\phi 15 \times 22.5mm$  with a longitudinal V groove (R0.15, depth 0.8, opening angle  $30^\circ$ ). Sequential upsettings were repeated until the crack size grew 0.5mm. After these sequential upsettings, the test pieces were observed with a scanning electron microscope (SEM) to investigate the void generation behavior in the vicinity of cracking.

As a comparison steel, SCM420 was prepared by spheroidizing annealing.

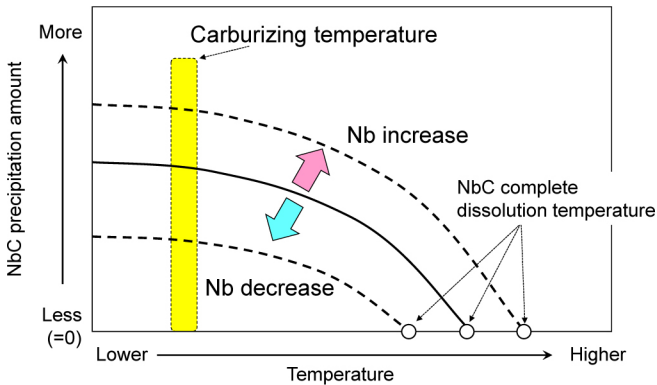


Figure 2. NbC precipitation curve.

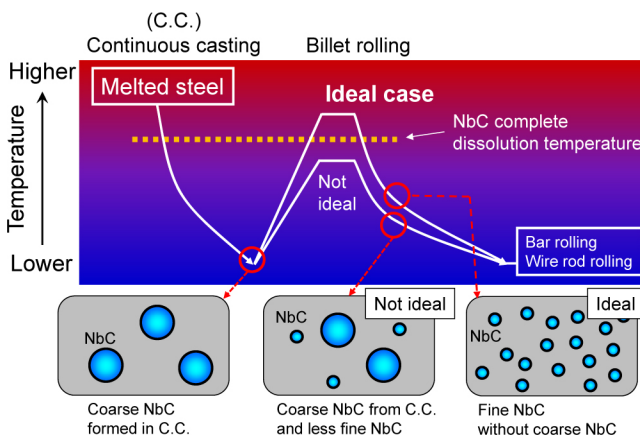


Figure 3. Control of NbC in manufacturing process.

## EXPERIMENTAL PROCEDURE FOR SUPPRESSION OF AUSTENITE ABNORMAL GRAIN GROWTH

A number of reports have been published on the solubility product of NbC<sup>28-29-30-31-32-33-34-35-36-37</sup>. However, different values have been reported by various researchers. Therefore, the optimal NbC solubility product in Nb-added carburizing steel was examined. Steels with different Nb contents were melted and subjected to heat treatments simulating billet rolling and steel bar rolling. The samples were then cold rolled at the total reduction of 50%, quasi-carburized at 1203K and held for 3h, followed by oil quenching. Precipitates were observed by transmission electron microscope (TEM) using samples prepared by carbon extraction replica method. The precipitation amount of Nb was determined by measuring the amount of Nb as Nb precipitates by chemical analysis of the residue obtained by electrolytic extraction.

In order to evaluate the suppression ability of the developed steel for abnormal grain growth of austenite, gear cold forging and quasi-carburizing were carried out. The quasi-carburizing temperature was 1203K, and the test pieces were held for 3h, followed by oil quenching. Normalizing was not performed. Figure 4 shows the shape of a gear produced by cold forging. The prior austenite grain

boundary was observed by optical microscopy after etching with an aqueous solution of picric acid with benzenesulfonic acid. The SCM420 comparison steel was also evaluated in the same manner.

## EXPERIMENTAL PROCEDURE FOR FATIGUE PROPERTIES OF DEVELOPED STEEL

Figure 5 shows the specimen shapes of the rotating bending fatigue test and the roller pitting fatigue test. Both tests were performed after carburizing quenching and tempering. The carburizing quenching was oil-cooled after holding at 1203K for 3 hours. Tempering was performed by air cooling after holding at 453K for 1 hour. The rotating bending fatigue test was conducted at about 3500 rpm. Comparison of grain boundary oxidation in the surface layer after carburizing was performed by Si concentration map obtained by electron probe micro analyzer (EPMA). The roller pitting fatigue test was set to about 1500 rpm with a sliding ratio of 40% and at 353K. Automatic transmission fluid was used for lubricating oil. For the large roller on the test machine side, carburized SCM 420 was used and the crowning radius of large roller was 150 mm.

## RESULTS AND DISCUSSION OF COLD FORGEABILITY

Figure 6 shows the microstructure after hot working by Thermecmaster. Steel A showed some bainite when hot worked at 1273K, but when hot worked at 1173K, a ferrite and pearlite structure with no bainite was observed. The ferrite fraction was 48.3% when hot worked at 1273K, but when hot worked at 1173 K, the ferrite fraction increased to 65.7%. Thus, an increase in the ferrite fraction was observed in the steel hot worked at lower temperature. Although the crystal grain size was refined in Steel A hot worked at 1173K, its hardness was reduced about  $\Delta HV40$  compared to the sample hot worked at 1273K. From this, in the range of the present study, the hardness decreases resulting from suppression of bainite and an increase in the ferrite fraction were more dominant than the hardness increase due to grain refinement.

Figure 7 shows the relationship between the hardness increase after hot rolling obtained by experiment and the amounts of Si, Mn and Cr. Addition of Si and Mn causes a large increase in hardness compared to addition of Cr. In order to ensure hardness after carburizing, hardenability is required in carburizing steel. Figure 8 shows the effects of Si, Mn and Cr on the hardenability index  $\beta$  value. Mn has the strongest effect on hardenability, but Cr is also effective. Si is apparently not effective.

From the above results, reducing Si and Mn but increasing Cr is a better alloy design for achieving both low hardness and sufficient hardenability. Reduction of Si is also preferable from the viewpoint of improving fatigue characteristics by contributing to suppression of grain boundary oxidation of the surface layer during carburizing<sup>38</sup>. Increasing Cr can be expected to improve pitting fatigue strength through improvement of tempering softening resistance<sup>39</sup>.