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Development of Middle-Carbon Steel Bars and Wire Rods for Cold Forging

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Abstract

Many mechanical parts for automotive power train and undercarriage are manufactured by forging, machining, and heat treatment using special steel bars and wire rods. Cold forging can give more precise dimensions than hot forging, therefore machining cost can be greatly reduced by converting hot forging to cold forging. Although Nippon Steel Corporation already developed softened low-carbon steels for cold forging by applying TMCP technology to bar and wire rod rolling processes, demands for middle-carbon steels for cold forging have arise recently. This paper outlines the development of middle-carbon steel bars and wire rods for cold forging "Super Forging steel (SF)".

1. Introduction

Many of the automotive parts applied to the undercarriages and powertrains(e.g., shafts, gears) are manufactured by forging, machining, and heat treating (annealing and carburizing) special steel bars and wire rods. Since the machining process that follows the forging process accounts for about 70% of the manufacturing cost of the parts, it is necessary to reduce the costs of the machining process. Cold forging offers higher dimensional accuracy of forged parts than hot forging and is expected to permit the omission of the finish machining process, as shown in **Table 1**. Therefore, there is growing demand for the application of cold forging to the automotive parts traditionally manufactured by hot forging. Since cold forging is subject to higher deformation resistance, it has been applied largely in the forging of parts of low-carbon steel or case hardening steel (0.1 - 0.3%C). However, even low-carbon steel and case hardening steel considerably shorten die life when used as-rolled. Therefore, it is necessary to anneal the steel material before subjecting it to cold forging. Intermediate annealing, which is performed between plural forging process, may be performed for the purpose of steel softening or stress relieving.

With the aim of omitting the annealing process in cold forging, Nippon Steel Corporation developed the concept of soft cold-forging steels referred to as Mild Alloy[1, 2] and Supermild Alloy;[3, 4] these

Table 1 Manufacturing processes of mechanical parts

Steel type	Process				
Low-carbon steel	Rolling	→	Hot forging	Machining	Carburizing
Low-carbon steel	Rolling	Annealing	Cold forging	→	Carburizing
Middle-carbon steel	Rolling	Annealing	Cold forging	→	Induction quench & tempering

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have already been applied in practice. The Mild Alloy, which is intended specifically for case-hardened parts, is manufactured by applying the so-called Thermo Mechanical Control Process (TMCP) technology in a bar and wire rod rolling process for JIS SCM420 and other low-alloy steels. By promoting the ferrite–pearlite transformation and implementing slow cooling, the formation of bainite is restrained, allowing omission of the annealing step after rolling. The Supermild Alloy, which is even softer than the Mild Alloy, is a low-alloy steel with optimized chemical composition. Namely, the contents of Si and Mn (solid solution strengthening elements) have been reduced to make the steel softer and B has been added to increase the ferrite volume fraction in the rolling process and secure adequate hardenability in the quenching process. Supermild SC is a carbon steel obtained by applying the above composition optimization technology.

Conversely, as shown in **Figs. 1** and **2**, middle-carbon steels (0.3 - 0.6%C) have low deformability and high deformation resistance compared to low-carbon and case hardening steels. Therefore, considerable technical difficulty and cost are involved in applying cold forging to middle-carbon steels. However, as shown in Table 1, parts made from middle-carbon steel can be imparted the required strength by induction quenching because of the relatively high carbon content (treatment time: several seconds to several minutes). Thus, applying cold forging to middle-carbon steels offers a major advantage by allowing for omission of the lengthy carburizing treatment (4 hours or so). Therefore, demand for the application of cold forging to middle-carbon steels has recently grown. In this technical report, we describe the Super Forging (SF) steel, a middle-carbon steel for cold forging that Nippon Steel Corporation has developed in response to the aforementioned demand.

2. Approaches to Improvement of Deformability and Reduction of Deformation Resistance of Cold Forging Steels

2.1 Relationship between deformability and microstructure

Middle-carbon steels were subjected to spheroidizing annealing (SA) immediately before they were cold forged; SA process results in a characteristic steel microstructure where spheroidal cementite is dispersed in a ferrite matrix. **Figs. 3** and **4** illustrate the influence of ferrite and cementite particle size on the critical upsetting ratio, obtained by an upsetting test of JIS S55C steel.[5] In the test, 10 mm (D) × 15 mm (L) cylindrical specimens with a notch (depth: 0.8 mm, ra-

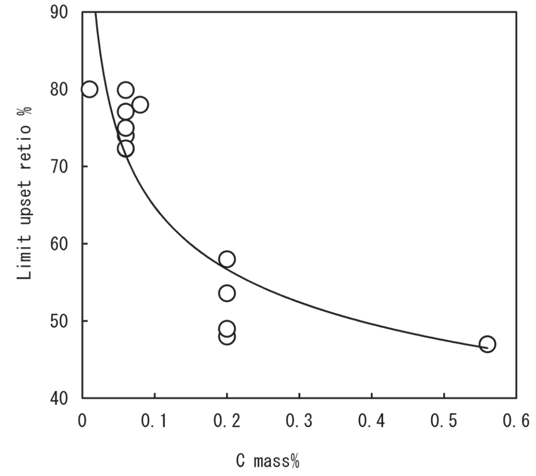


Fig. 1 Influences of carbon concentration on the deformability

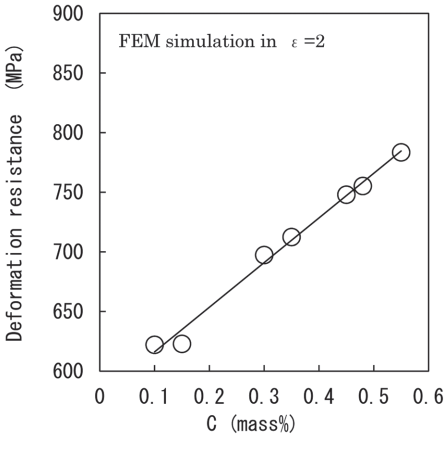


Fig. 2 Relationship between deformation resistance and carbon concentration

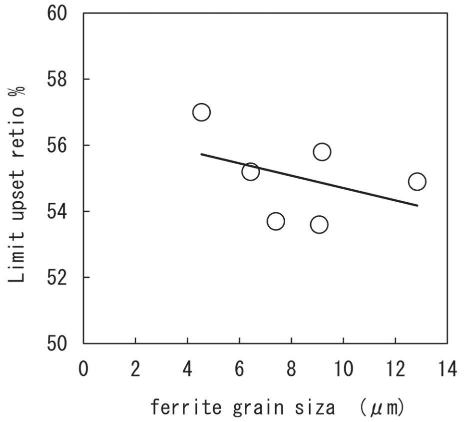


Fig. 3 Influences of ferrite grain size on deformability

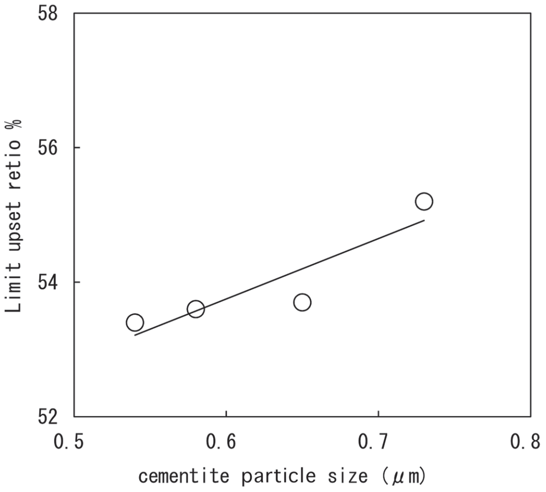


Fig. 4 Influences of cementite particle size on deformability

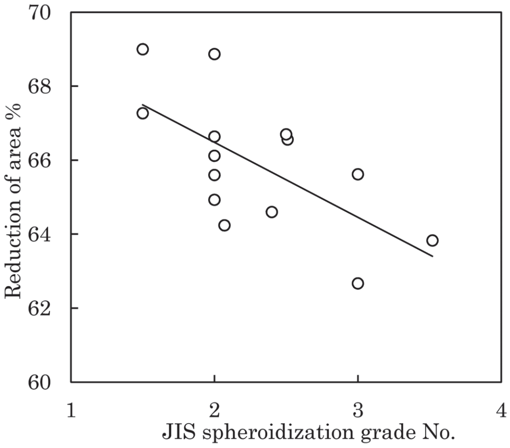


Fig. 5 Relationship between reduction of area and spheroidization degree

dius of curvature: 0.15 mm) were compressed with the end constrained with a grooved base. Using the specimen height before deformation (H_0) and the specimen height at the critical upsetting ratio for crack initiation (H), the critical upsetting ratio (%) was calculated as (H_0 − H) / H_0 × 100. **Fig. 5** illustrates the relationship between the degree of cementite spheroidization and the reduction of area. The degree of spheroidization was obtained using the method specified in JIS G 3539. The smaller the JIS spheroidization number, the better the spheroidized microstructure. It can be seen from the above figures that it is possible to increase the critical upsetting ratio and the reduction of area by refining ferrite grains, coarsening cementite particle, and improving the degree of spheroidization.

2.2 Relationship between deformation resistance and microstructure

The deformation resistance of a steel material depends on its hardness and work hardening behavior. Since the influence of steel hardness is particularly strong, it is important to soften the steel to reduce its deformation resistance. Using JIS S55C steel that had been subjected to SA, the individual strengthening factors of ferrite grain size, cementite particle size, and ferrite matrix composition were evaluated. The amount of solid solution strengthening was calculated using the ferrite equilibrium composition at 300°C (C = 1.3 × 10^{-5} wt%, Cr = 0.08 wt%, Mn = 0.25 wt%), obtained using Thermo-Calc. It was assumed to be 55 MPa on the basis of data presented in the literature.[6)] The amount of grain refinement strengthening was calculated by substituting the modulus of rigidity (G, 80 GPa), the critical strength of the ferrite grain boundary (τ^*, 4.5 GPa),[7)] the Burger's vector derived from the lattice constant of iron (b, 0.25 nm), and the average ferrite grain size (d_α) into the following equation of Hall–Petch type.

$$\sigma_y = 2\sqrt{\frac{Gb\,\tau^*}{d_\alpha}} \quad (1)$$

The amount of particle dispersion strengthening was calculated by substituting G, b, the coefficient of linear tension of dislocation (β, 0.8),[8)] the theoretical volume fraction of cementite (f, 0.079) derived from a phase diagram, and the average cementite particle size (d_θ) into the following equations.[8)]

$$\lambda = \left(1.25\sqrt{\frac{\pi}{6f}} - \frac{\pi}{4}\right) d_\theta \quad (2)$$

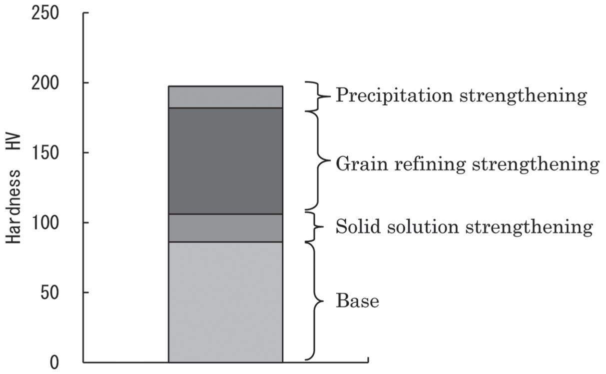


Fig. 6 Hardness of the spheroidizing annealed steel (JIS S55C)

$$\sigma_y = \frac{4\beta Gb}{\lambda} \quad (3)$$

The above theoretical equations calculate yield stress (σ_y), which needs to be converted to the hardness value. The tensile strength (kgf/mm^2) displays a correlation with hardness (approximately equal to 1/3 of the hardness) and can be approximated empirically as yield stress + 130 MPa. Hence, the theoretical equation was converted as follows.

$$HV = \frac{\sigma_y + 130}{9.8 \times 3} \quad (4)$$

The amount of dislocation strengthening was not considered because the dislocation density was assumed to have been lowered sufficiently by SA.

Fig. 6 shows the results of strength calculations performed using the above procedure. Ferrite grain refining strengthening is the most conspicuous, followed by solid solution strengthening and cementite dispersion strengthening. Therefore, the softening of steel by coarsening ferrite grains is particularly effective in reducing the deformation resistance of steel. Cold forging cracks often occur when the surface layer of the steel material is subjected to strong working, such as in upsetting, flanging, or heading. It is therefore possible to attain both high deformability and low deformation resistance of the steel material to be processed by refining ferrite grains and coarsening cementite particles in the surface layer that is required to have good deformability and by coarsening ferrite grains in the central portion that is not required to have good deformability. By applying the technology established in the development of Supermild Steel, that is, by reducing the contents of Si and Mn (solid solution strengthening elements) and adding B (an element that contributes little to solid solution strengthening) to compensate for the decline in hardenability, it is possible to reduce the deformation resistance further still.

3. Super Forging (SF) Steel Manufacturing Process

In order to obtain a rolled steel bar with good cold forgeability, as described in the preceding section, Nippon Steel Corporation designed a new process that combines controlled rolling with the bar direct surface quenching (DSQ) equipment[9)] and off-line SA, thereby developing Super Forging (SF) steel with its superior cold forgeability.

3.1 Controlled rolling and DSQ

Fig. 7 illustrates the layout of the equipment in the Muroran Bar

Mill. The rolling equipment consists of compact roughing mill (4-pass), intermediate mill (4-pass), No. 1 finishing mill (4-pass), No. 2 finishing mill (6-pass), and reducing & sizing block (RSB; 3-roll, 4-pass). The intermediate water jackets provided between the mills allow for highly efficient controlled rolling. The RSB is a high-rigidity mill that is capable of securing the high dimensional accuracy required of cold forging steel even in controlled rolling.[10] DSQ water jackets are installed immediately after the No. 2 finishing mill to allow for efficient cooling after controlled rolling. The rolled steel bar is threaded through the DSQ water jackets for accelerated cooling and surface quenching. After the steel bar passes through the DSQ water jackets, it tempers itself by the sensible heat of its interior. As shown in **Photos 1** and **2**, the surface layer has a microstructure of tempered martensite or bainite and the central portion has a ferrite–pearlite microstructure.

3.2 Spheroidizing annealing (SA)

Ordinarily, SA of middle-carbon steel is performed in the heat pattern of the so-called slow cooling process, as shown in **Fig. 8**.

① The surface layer of SF steel has a quenched microstructure, whereas the microstructure of conventional steel before SA is ferrite–pearlite.

② The steel is heated to the two-phase region above the A_1 temperature. The cementite is not melted completely. Instead, part of the cementite is allowed to reside in the steel.

③ The steel is cooled at a rate at which spherical cementite can grow from the residual cementite as the nucleus, thereby coarsening the cementite particles.[11, 12]

In order to obtain the unmelted cementite to reside during the retention of SA heat in ② , about 0.1% Cr is added to the steel to stabilize cementite.[13] If Cr is not added, cementite melts completely during the retention of SA heat and pearlite (regenerated lamellar) is generated in the slow cooling process.

When a ferrite–pearlite structure is subjected to SA, lamellar cementite remains if the cementite in the pearlite is not melted completely. Conversely, the number of nuclei for growth of spherical cementite decreases if the cementite is overly melted. In those cases, pearlite (regenerated lamellar) tends to be generated easily during slow cooling. It is therefore difficult to obtain a microstructure which is free of lamellar cementite and high degree of spheroidization by steels which have pearlite structure were subjected to SA.

In the case of SF steel, however, the microstructure of the surface layer before SA is a tempered martensite or bainite structure that has been obtained by DSQ. Therefore, lamellar cementite does not remain, but a part of cementite which is precipitated by self-tempering remains during the retention of SA heat. Namely, It is possible to obtain a microstructure in which cementite with high degree of spheroidization is uniformly dispersed by growing spherical cementite particles from the residual cementite as nuclei during slow cooling. The microstructure of the central portion before SA is not a quenched structure but a ferrite–pearlite structure. Therefore, even after SA, the ferrite grains in the central portion are coarser than those in the surface layer.

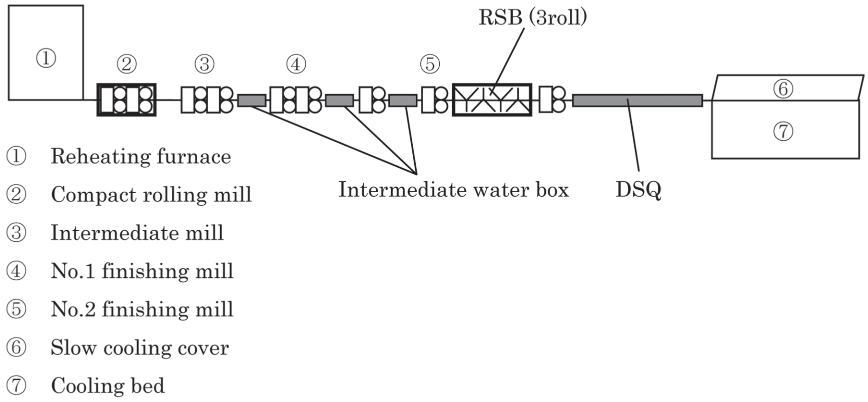


Fig. 7 Layout of Muroran bar mill

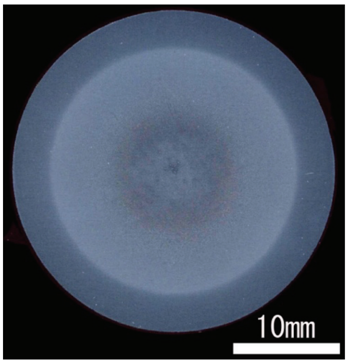


Photo 1 Macrostructure (30mmφ, JIS S45C)

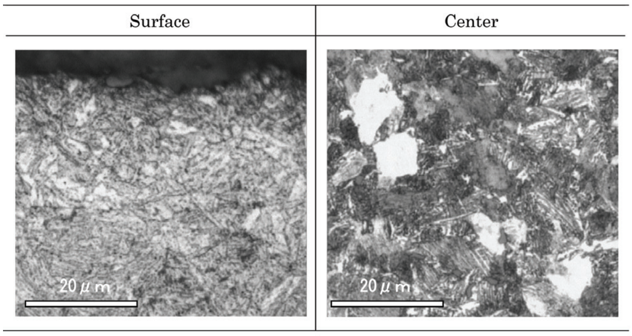


Photo 2 Microstructure (30mmφ, JIS S45C)

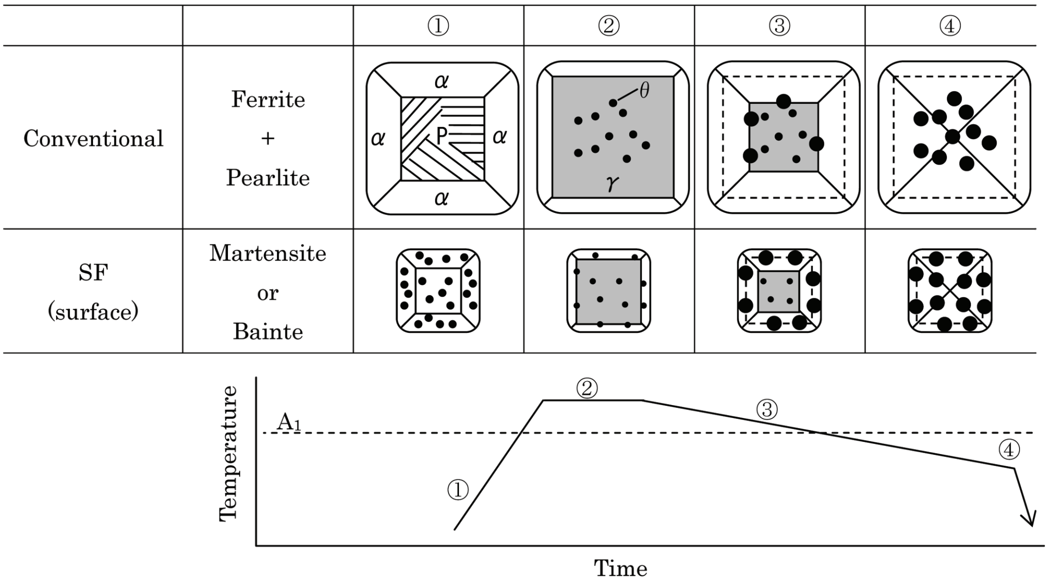


Fig. 8 Spheroidizing mechanism of cementite in annealing process

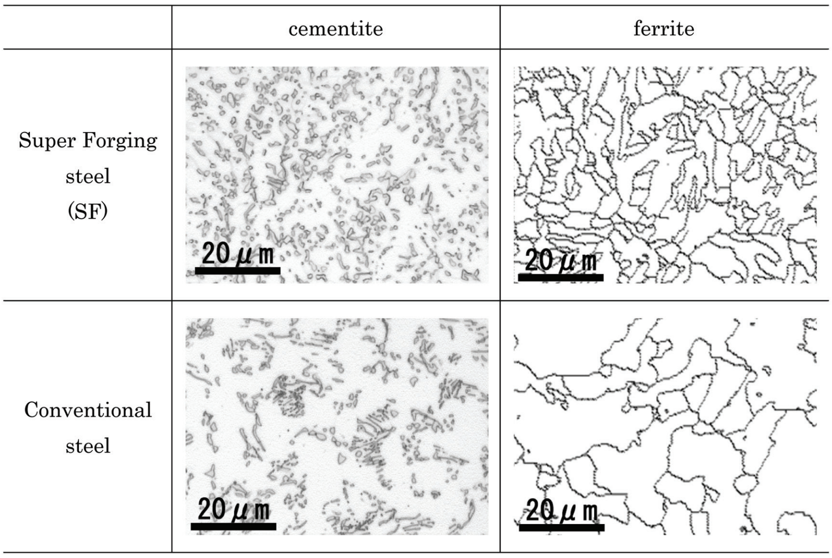


Photo 3 Surface microstructure after spheroidizing annealing

4. Microstructure, Deformability, and Deformation Resistance of Super Forging Steel

Photo 3 shows the results of observation of cementite and ferrite in the surface layer of SF steel and conventional steel, both of JIS S55C, after SA. The cementite was observed using an optical microscope and the ferrite using a scanning electron microscope (SEM)—electron back scattering diffraction (EBSD), with a crystal misorientation angle of 15° or more considered to represent a grain boundary. It is clear that, unlike conventional steel, the SF steel is free of lamellar cementite and contains uniformly dispersed cementite particles and refined ferrite grains.

Fig. 9 illustrates the critical upsetting ratio of SF and conventional steels. It is clear that the critical upsetting ration of the SF steel is about 6% higher than that of the conventional steel; hence, it shows

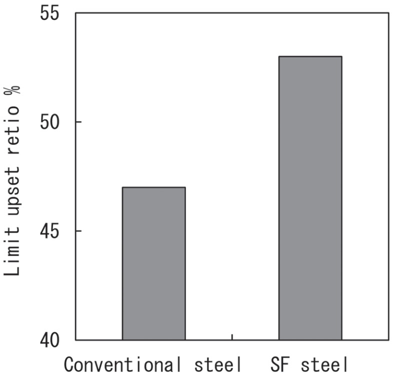


Fig. 9 Deformability of the conventional steel and super forging steel (SF)

better deformability. **Fig. 10** shows the deformation resistance of the SF and conventional steels, indicating that both steels exhibit comparable deformation resistance. It is expected that the application of SF steel will increasingly be applied to cold forged parts which required a high degree of working, also will permit omission of the intermediate annealing process for parts which have been already applied to cold forging. Using a combination of Supermild SC—a softened steel whose composition has been optimized through the reduction of Si and Mn contents and the addition of B—and SF steels, it is possible to improve the deformability and reduce the deformation resistance simultaneously. **Fig. 11** shows the deformation resistance of conventional JIS S48C steel and Supermild SC + SF steel. The combination of Supermild SC + SF steel exhibits smaller deformation resistance than conventional steel; it is expected that this will help prolong die life without causing the deformability of the steel material to deteriorate.

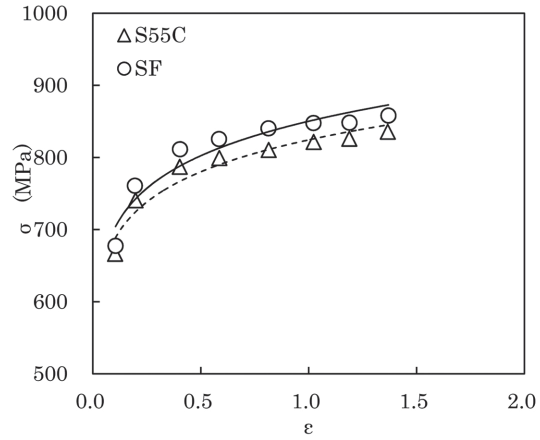


Fig. 10 Deformation resistance of the conventional steel and super forging steel (SF)

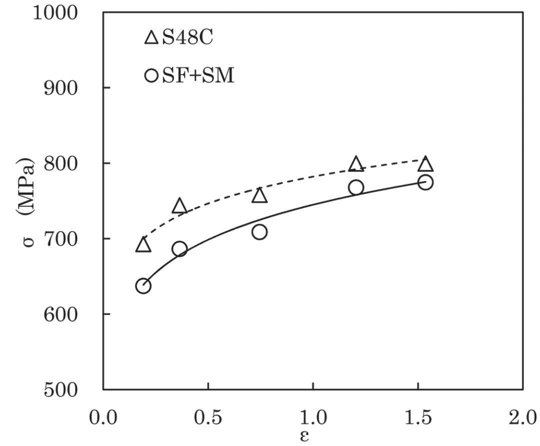


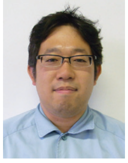
Fig. 11 Deformation resistance of the super forging steel (SF) + super mild SC steel (SM)

5. Conclusions

We have described the development of the Super Forging (SF) steel, a middle-carbon cold forging steel that should reduce the manufacturing costs of automotive parts and save energy. It has become essential to omit the annealing and machining processes and the requirements of steel materials have become increasingly sophisticated. We believe that it will become even more important in future to simplify or omit processes in the manufacture of automotive parts by making the most effective use of the superior properties of newly developed steels such as the SF steel.

References

1) Naito, K., Mori, T., Okuno, Y., Yatsuzuka, T., Ebihara, T.: CAMP-ISIJ. 2, 1752 (1989)
2) Okatoshi, H., Kumano, K., Nakamura, K., Nashimoto, K., Matsumoto, T., Baba, M., Sasaka, S.: Shinnittetsu Giho. (343), 63 (1992)
3) Tarui, T., Tashiro, H., Sato, H., Takahashi, N.: CAMP-ISIJ. 2, 1760 (1989)
4) Ochi, T., Takada, H., Kubota, M., Kanisawa, H., Naito, K.: Shinnittetsu Giho. (370), 11 (1999)
5) Materials Research Group of Cold Forging Sectional Committee: Plasticity and Working. 22, 139 (1981)
6) The Japan Institute of Metals: Steel Materials—Modern Metal Science, Materials Volume, 4.2 Edition. Tokyo, Maruzen Publishing Co., 1985, pp. 57, 87
7) Takaki, S.: 191st/192nd Nishiyama Memorial Lectures, compiled by the Iron and Steel Institute of Japan. 2007, p. 2
8) Kitaura, T., Tobitaka, H., Tsuchiyama, S., Takagi, S.: Tetsu-to-Hagané. 91, 796 (2005)
9) Anzawa, N., Yazaki, H., Takahashi, T., Sakaguchi, S., Hasegawa, K., Harada, T.: Tetsu-to-Hagané, 73, S1136 (1987)
10) Seki, R., Hasegawa, K., Nakajima, K., Yoshimura, K.: Shinnittetsu Giho. (386), 20 (2007)
11) Ochi, T., Koyasu, Y., Mori, T.: Heat & Surface '92 Kyoto. 1992, IFH-TSE
12) Ochi, T., Mori, T., Okuno, Y.: CAMP-ISIJ. 3, 1830 (1990)
13) Ochi, T., Koyasu, Y.: CAMP-ISIJ. 4, 2046 (1991)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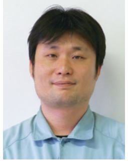
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