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High-Carbon Steel Sheets for Power Train Parts —Formable High-Carbon Steel Sheets Suitable for One-Piece Forming—†

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Abstract:

JFE Steel has developed two types of formable high-carbon steel sheets for automotive power train parts which are suitable for one-piece forming. The non-oriented high-carbon cold-rolled steel sheet has extremely low planar anisotropy of the r-value (Δr = 0.06), resulting in high formability, and excellent hardenability in low-temperature, short-time heat treatment. This new sheet displays high dimensional accuracy in press forming of cylindrical rotating parts. Hyper-burring high-carbon hot-rolled steel sheet (Hyper-Burring SC) has excellent burring properties (hole expansion, punching) due to fine dispersion of spheroidized cementites, which was made possible by applying a rapid cooling system (Super-OLAC H) in the run-out table of the hot-rolling process, and is an optimum product for thickness-addition forming.

1. Introduction

The key issues for technical development in the field of automotive power train parts for simultaneously satisfying the requirements of low fuel consumption and cost competition in the global market include: (1) improved power train efficiency (reduced rotational resistance), (2) weight reduction without sacrificing high durability, and (3) improved dimensional accuracy and reduction of excess material in parts. Power train parts must possess both high accuracy and high strength, and because the production process consists of many individual processes such as forming, welding, and hardening, processing costs account for a large percentage of the total part cost in comparison with material costs. Automakers are therefore actively introducing methods which reduce production costs by (1) one-piece forming, which reduces the number of individual parts and saves joining costs, and (2) omission of shape reforming/trimming and intermediate annealing in the forming process.

As a solution to these problems, this paper describes two types of formable high-carbon steel sheets which enable one-piece forming of automotive power train parts.

2. Non-Oriented High-Carbon Cold-Rolled Steel Sheet[1-3)]

High-carbon cold-rolled steel sheets are widely used in automotive power train parts which require excellent formability and thickness accuracy. However, when forming cylindrical, axially-symmetric parts, anisotropy in a designated plane in the rolled steel sheet causes the following problems, which made subsequent shape reforming or machining processes unavoidable:

(1) Earring, which reduces yield
(2) Reduced circularity, which causes eccentricity during rotation
(3) Thickness deviations, which cause non-uniform hardening

To solve these problems by reducing planar anisotropy, the authors developed a new high-carbon cold-

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rolled steel sheet which possesses both the essential property of press formability and high induction-hardenability.

2.1 Development Concept

Planar anisotropy in steel sheets is defined by the r-value ($= \{\ln(w_0/w)\} / \{\ln(t_0/t)\}$, where w is width and t is thickness). The degree of earring during cup-forming of a steel sheet decreases as the planar anisotropy of the r-value ($\Delta r = (r_{0°} + r_{90°} - 2r_{45°})/2$) approaches 0. Planar anisotropy is strongly correlated with the recrystallization texture.[4] In containers, improved planar anisotropy is achieved by increasing cold reduction to as much as 90% as a method of controlling the recrystallization texture.[5] However, in transmission part applications, the increase in cold reduction is not desirable because it is essential to secure a certain sheet thickness.

Due to the relationship between the rolling direction of respective crystal orientations and the r-value,[6] the sheets in which the {111} orientation is developed in the sheet plane show high r-values in all directions in the sheet plane. In contrast, with the {100}<011> orientation, the r-value is high in the 45° direction, and with the {110}<001> orientation (Goss orientation), $r = 0.5$ in the 0° direction and the r-value becomes infinitely large in the 90° direction, seriously reducing planar anisotropy.

The authors therefore conjectured that the planar anisotropy of the r-value in high-carbon steel sheets could be effectively improved by randomizing the development of the <111>//ND (normal direction), which is the priority orientation, and controlling the morphology of cementite, which has an important effect on recrystallization and grain growth, in order to suppress the development of the {110}<001> Goss orientation (r-value in 90° direction relative to rolling direction: infinite) as an impediment to the planar anisotropy of the r-value.

2.2 Texture Control

2.2.1 Improvement of planar anisotropy

To investigate the effect of the cementite diameter on recrystallization and texture, the cementite diameter was varied by performing annealing for 40 h at 640°C (steel A) and 720°C (steel B), which are below the A_{c1} transformation point, prior to cold rolling. The material used was commercially-manufactured JIS S35C hot band. Cementite was 100% spheroidized in both cases, and had diameters of steel A: 0.4 μm and steel B: 1.0 μm, respectively. The samples were then cold-rolled at a reduction of 70%, and the resulting sheets were subjected to recrystallization annealing for 40 h at 680°C. In steel A, which had a submicron-size cementite diameter, planar anisotropy was extremely small, at $\Delta r = 0.03$. In contrast, steel B showed large planar anisotropy, at $\Delta r = 0.12$, demonstrating that the cementite diameter as a large influence on the planar anisotropy of the r-value. It should also be noted that no difference in texture attributable to hot-band annealing was observed. Based on this fact, it was considered that submicron-size cementite has some type of effect on the formation of <111>//ND grains, and the recrystallization texture was therefore investigated from this viewpoint.

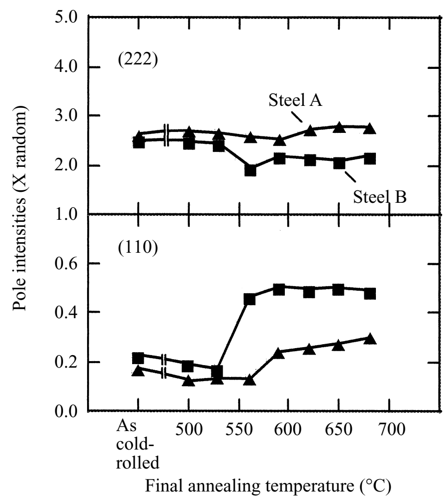

Fig. 1 Changes of normalized relative values of integrated X-ray intensities ((hkl)) during 2nd annealing

From the integrated X-ray intensities during the second annealing as shown in **Fig. 1** and the ODF (orientation distribution function) analysis results after the second annealing, steel A, in which cementite is finely dispersed, maintains the {111} orientation at a high level, and simultaneously the development of the {110}<001> Goss orientation, which impairs planar anisotropy, is significantly reduced. This is attributed to the fact that fine cementite promotes randomization of {111} grains by suppressing preferential consumption of {111}<112> grains by Goss grains, and thus greatly reduces the anisotropy of <111>//ND fiber.

2.2.2 Role of cementite in recrystallization and texture formation

The morphology and amount of precipitation of cementite, which is the second phase, affect recrystallization and texture formation in high-carbon cold-rolled steel sheets. Because cementite is extremely hard (HV = 950) in comparison with the ferrite matrix, cold rolling generates high strain in ferrite in the vicinity of cementite boundaries. The existence of this region has an important effect on recrystallization behavior. Furthermore, cementite diameter and dispersion characteristics also have a considerable effect on ferrite grain growth.

Photo 1 shows the microstructural change after cold

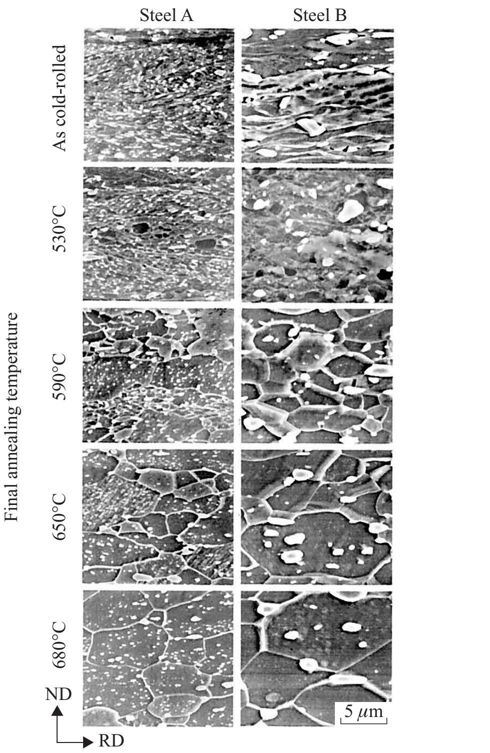

Photo 1 Effect of annealing temperature prior to cold-rolled on microstructural change during final annealing

rolling and during the second annealing.[7,8] The effect of the annealing temperature prior to cold rolling on microstructural change during the final annealing can be understood from these photos. Specifically, in steel B, which has large planar anisotropy, a fine recrystallization structure can be observed at 530°C, and recrystallization is completed at 590°C. This indicates that steel sheets containing coarse cementite display the same mode of recrystallization grain growth as those which do not contain the second phase. In this case, it is considered that Goss grains are formed from high strain areas corresponding to the deformation bands in ferrite grains[9] and consume the {111} grains developed during cold rolling. On the other hand, in steel A, which has small planar anisotropy, even though partial recrystallization begins at 530°C and small crystallized grains can be observed partially at 590°C, the steel assumes a mixed-grain structure consisting of extremely large recrystallized grains (center photo) and a fine unrecrystallized structure. From Fig. 1 and Photo 1, it is considered that the {111} and {110} orientations developed during cold rolling are maintained by *in-situ* recrystallization,[10] but {111} grains then grow by abnormal grain growth accompanying coarsening of cementite in the subsequent heating-up stage, while achievement of {110} grains is suppressed. The fact that some slight achievement of the Goss orientation can be observed is attributed to the partial formation of recrystallized grains (small recrystallized grains which formed at 590°C), as in steel A, and corresponds to this phenomenon.

2.3 Properties of Non-Oriented High-Carbon Cold-Rolled Steel Sheet

2.3.1 Microstructure and mechanical properties of developed steel

The typical microstructure and mechanical properties of the newly developed JIS S35C equivalent steel are shown in **Photo 2** and **Table 1**, respectively. The developed steel has a microstructure consisting of homogeneously equiaxed ferrite grains and finely dispersed cementite, and possesses excellent formability, displaying an elongation (El) value of 39%. The tensile strength (TS) is 470 MPa, and its Vickers hardness (HV) is 140. The planar anisotropy of the r-value (Δr) is extremely small, at 0.06.

2.3.2 Formability and dimensional accuracy of developed steel

The appearance of the developed and the conventional steels after cylindrical deep drawing is shown in **Photo 3**. The blank size was 100 mm in diameter, and the drawing ratio was 2.0. **Figure 2** shows the change in wall height and wall thickness in the circumferential direction. The developed steel, which has extremely small planar anisotropy, showed little deviation in wall height, at a maximum value of approximately 0.5 mm, even in deep drawing at a drawing ratio of 2.0, which allows users to substantially rationalize the machining/trimming process. Furthermore, with the developed steel, the deviation in wall thickness was less than 1% (10–20 μm), even at the 30 mm drawing height position, in contrast to a maximum thickness deviation of 6% with the conventional steel. Thus, reforming is also unnecessary with the developed steel due to its excellent

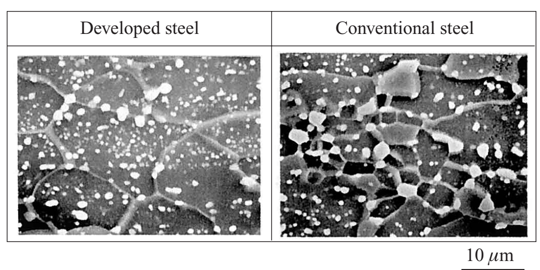

Photo 2 Microstructures of steels

Table 1 Mechanical properties of steels

	YP (MPa)	TS (MPa)	El (%)	$r_{0°}$	$r_{45°}$	$r_{90°}$	Δr	mean-r
Developed steel	380	470	39	1.06	0.98	1.01	0.06	1.01
Conventional steel	290	500	35	1.25	0.95	1.38	0.37	1.14

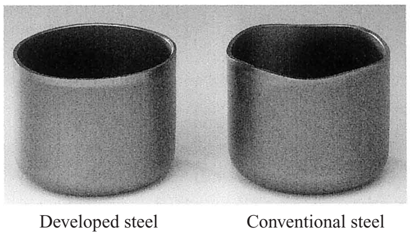

Photo 3 Appearance of cup cylinder tested pieces

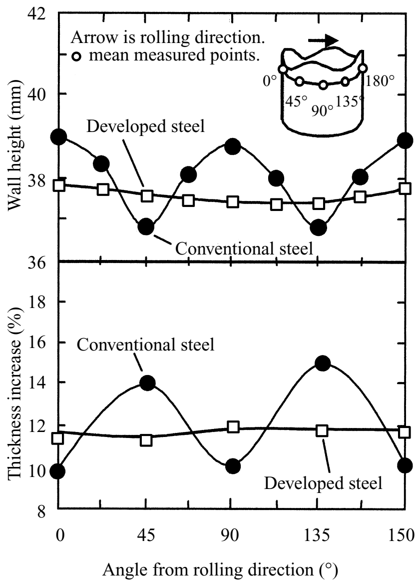

Fig. 2 Change in wall height and wall thickness

thickness accuracy.

The most critical property for power train parts is circularity. As can be seen in **Fig. 3**, in the cup cylinder test, the conventional steel showed large deviations in outer diameter at a 45° pitch, corresponding to the wall height and thickness addition. In contrast, the developed steel was virtually free of deviations in outer diameter over the entire 360° circumference. (The broken lines in Fig. 3 show true circularity.) Thus, the developed steel displays excellent circularity after drawing, eliminating the need for a shape reforming process. Moreover, because the developed steel also possesses high elongation, it has excellent press formability and can be

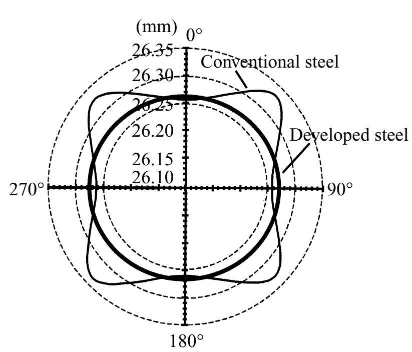

Fig. 3 Appearance change of test pieces after cup cylinder test

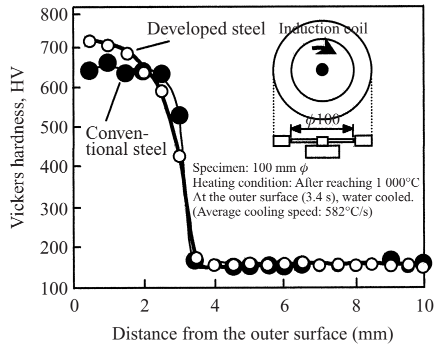

Fig. 4 Hardness distribution after induction heating

applied to the parts with complex shapes.

2.3.3 Hardenability of developed steel

A hardenability evaluation was performed using 100 mm in diameter blanks finished by machining the edges. While rotating the samples at 70 rpm, the outer edge was rapidly heated to 1 000°C with an induction heating device. The samples were then quenched in water, and their hardness distribution was measured. **Figure 4** indicates that the developed steel has excellent hardenability, displaying an HV value 80 points higher than that of the conventional steel at the extreme surface layer on the outer circumference, which is essential for wear resistance. Thus, reducing the cementite diameter to the submicron size not only enables texture control, but also improves low-temperature, short-time hardenability. As practical benefits, adoption of low-temperature, short-time heat treatment reduces thermal strain in the product, while also contributing to higher productivity and energy saving.

2.4 Examples of Application

At present, the non-oriented high-carbon cold-rolled steel sheets have been commercialized in grades from S35C to SK5. Application is being promoted in multiple directions from the viewpoints of excellent formability and hardenability as well as uniform mechanical properties. As examples, the S35C material is applied to the one-piece drive plate with ring gear and SK5 in bearing parts.

3. High-Carbon Hot-Rolled Steel Sheet with Excellent Stretch-Flange Formability (Hyper Burring SC)

Conventionally, many automatic transmission clutch hub/drum and planetary carrier parts have been manufactured by press-forming the cylindrical parts from low-carbon hot-rolled steel, while producing cast and forged parts for bosses separately from special steel, and then joining the respective parts by electron beam welding. One-piece forming from steel sheets has been progressively adopted in recent years, but in many cases, low-carbon hot-rolled steel sheets with high formability are used as the material. In hydraulic parts for CVT, post-thickness addition is possible by performing compressive forming on a cup-shaped sheet while simultaneous expanding the cylindrical part.[11] With complex-shaped parts of this type, excellent formability is also a requirements for boss forming and thickness addition when performing one-piece forming and post-heat treatment with high-carbon steel sheets, for example, as seen in drive plates. In particular, burring formability and a high deformation capacity (local ductility) during heavy forming are essential. To meet these requirements, the authors developed a hot-rolled high-carbon spheroidizing annealed steel sheet with an excellent hole-expansion property by applying microstructural control using a rapid cooling system in the run-out table of the hot-rolling process.

3.1 Features of Hot-Rolled High-Carbon Steel Sheet with Excellent Stretch-Flange Formability

3.1.1 Microstructure and mechanical properties

Table 2 shows the chemical compositions of the developed JIS S35C equivalent high-carbon steel sheet with an excellent hole-expansion property and the conventional one. In both steels, the content of S, which has a large effect on the hole-expansion property,[12] is 0.002 mass%. The in microstructure and mechanical properties are shown in **Photo 4** and **Table 3**, respectively. The developed steel consists of uniform fine ferrite grains, and cementite is uniformly and finely dispersed by nearly 100% spheroidization. In contrast, the cementite in the conventional steel is dispersed non-uniformly, and furthermore, remains in lamellar form. The developed steel has excellent formability, with a hole-expanding ratio (λ) of 80% and high elongation of 38%. In the hole-expansion test, a flat punch was used in consideration of forming conditions and the fact that the sheet thicknesses applicable to power train parts are large, and burr due to punching punch was evaluated on the die side. **Photo 5** shows the cross-sectional microstructure in the vicinity of the punched edge in the hole-expansion test. With the conventional steel, voids following band-like lamellar cementite are already interconnected in the punching step, prior to hole expansion, which results in cracking. In contrast, with the developed steel, which has a high hole-expansion property, only very slight occurrence of voids could be observed.

In the post-heat treatment made by induction heating, there are cases in which parts are required to provide strength of the 440 MPa level, including non-heat treated areas, and in this case, the strength-λ balance becomes important. **Figure 5** shows the balance of properties in the developed steel. It satisfies the hardness requirement for the JIS S35C cold-rolled spheroidizing annealed material at HV: 170 or less, and has a high hole-expansion property while also securing tensile strength (TS) of 440 MPa. Based on these properties, high durability can be obtained in non-heat treated parts, allow-

Table 2 Chemical composition of steels

(mass%)

	C	Si	Mn	P	S
Developed steel	0.33	0.19	0.74	0.017	0.002
Conventional steel	0.34	0.18	0.76	0.017	0.002

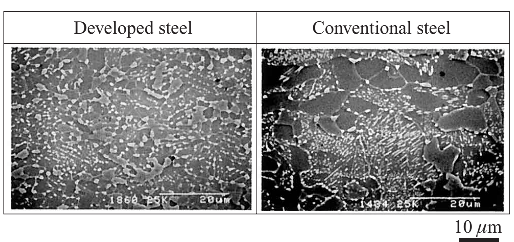

Photo 4 Microstructures of steels

Table 3 Mechanical properties of steels

	YP (MPa)	TS (MPa)	El (%)	λ* (%)	Hardness, HV/HRB
Developed steel	386	488	38	80	150/78
Conventional steel	317	506	33	44	156/82

* Hole expansion ratio, Clearance: 20%

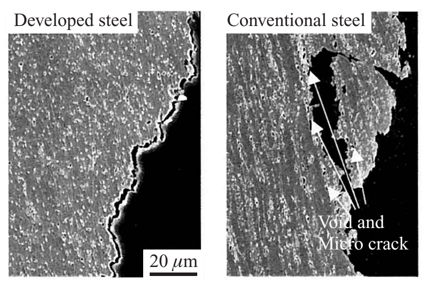

Photo 5 Microstructures of steels

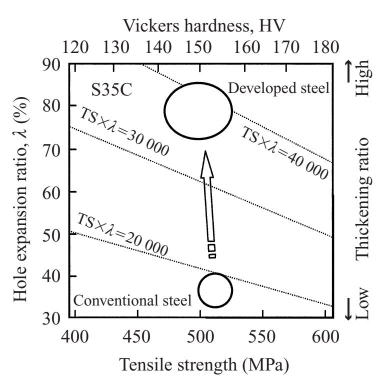

Fig. 5 Comparison of hole expansion ratio-strength balance of S35C hot rolled steels

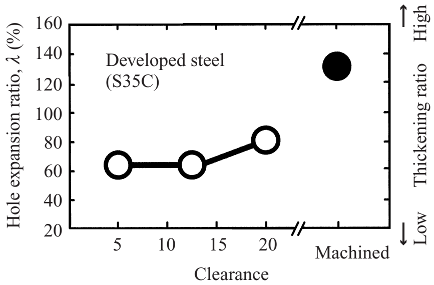

Fig. 6 Effect of clearance and machined on hole expansion ratio

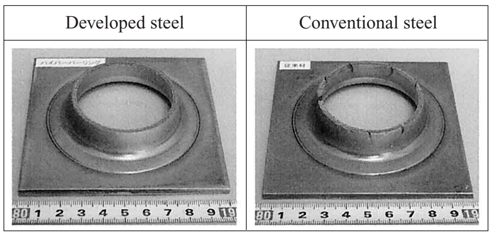

Photo 6 Hole expanded test piece (S35C)

ing gauge reduction (reduction of excess material thickness).

It has long been known that the hole-expansion property is affected by the punching clearance. Likewise, with this newly developed high-carbon steel sheet, **Fig. 6** shows that the hole-expansion property is approximately $\lambda = 60\%$ at clearances of 5% and 12.5%, but improves to $\lambda = 87\%$ at a clearance of 20%. With machined holes (reaming in circumferential direction), the hole expansion property is excellent, at $\lambda = 147\%$, because damage to the edge surface is extremely slight.

3.1.2 Simulated forming of boss parts

The appearance of samples after a hole-expanding test simulating boss forming is shown in **Photo 6**. Although difficult with the conventional steel, the possibility of boss forming is greatly increased with the developed high-carbon steel sheet, and the one-piece forming and post-thickness addition are easy. Due to uniform fine dispersion of cementite carbides, the developed steel also has excellent low-temperature, short-time hardenability with induction heating and possesses excellent punchability and uniformity in punched edges.

3.2 Examples of Application

Because the developed steel has excellent thickness addition formability by press forming and cold forging, application to numerous parts which require post-thickness addition is under study. Examples include the clutch hub/drum, planetary carrier, CVT piston, and one-piece drive plate with ring gear.

4. Conclusion

As materials for automotive power train parts, two types of new formable high-carbon steel sheets for one-piece forming were developed by controlling the recrystallization texture and microstructure using JIS S35C, as summarized below.

(1) The non-oriented high-carbon cold-rolled steel sheet features extremely small planar anisotropy of the r-value (Δr) and has excellent formability and hardenability with low-temperature, short-time heating. It is suitable for parts which require high dimensional accuracy.

(2) The hot-rolled high-carbon steel sheet with excellent stretch-flange formability (Hyper-Burring SC) possesses an excellent burring property and punchability as a result of structural control by a rapid cooling system in the run-out table of the hot-rolling process, and is an optimum material for differential-thickness parts manufactured by thickness-addition forming.

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