Technical Report

Development of High Purity Ferritic Stainless Steel Bar and Wire Rod for Fuel Components and Processing Technology

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Abstract

With the spread of direct injection gasoline engines against a background of higher efficiency, the importance of the quality and reliability of the high purity ferritic stainless steel large-diameter bar and wire rod, which is suitable for the high-pressure fuel pumps and injectors that make up these components, is expected to increase. In this study, the quality and functionality of NSSC180 large-diameter bar and wire rod made of high purity ferritic stainless steel were investigated. Coarse grain structure hinders ultrasonic testing performance, so it is necessary to reduce the grain size, and large-strain working using gradient rolling accelerates recrystallization and reduces grain size, improving ultrasonic testing performance and toughness. In addition, forming at appropriate forging temperatures results in high strength and excellent soft magnetic properties with the omission of magnetic annealing. This is expected to improve the high quality and reliability of fuel components.

1. Introduction

In recent years, the market introduction of electric vehicles has been active, but it is expected that the majority will continue to be equipped with internal combustion engines,[1–3] and the high efficiency of gasoline engines is being investigated.[3] In gasoline vehicles, high-pressure fuel systems are being adopted to enhance combustion efficiency, aiming to meet environmental regulations and improve fuel economy. Direct-injection gasoline engines are considered the mainstream technology.[4] These engines consist of components such as high-pressure fuel pumps and injectors,[5] where stainless steel large-diameter bar and wire rod is widely used. High-pressure fuel pumps and injectors are assembled through welding numerous components.[6,7] With increasing fuel pressure,[8,9] higher material reliability (corrosion resistance, strength, etc.) is required. Furthermore, the magnetic circuit components of injectors use electromagnetic valves controlled by electronic circuits for precise fuel injection, necessitating soft-magnetic properties in these materials.[10]

High-purity ferritic stainless steels exhibit excellent corrosion resistance, heat resistance, oxidation resistance, etc., making them widely used in kitchen appliances and automotive exhaust system components.[11–13] Furthermore, high-purity ferritic stainless steels offer superior corrosion resistance at welded joints and possess properties like soft magnetic characteristics,[14] making them suitable for the aforementioned fuel system component applications. The high-purity ferritic stainless steel NSSC180 is a material based on 19Cr, optimized for formability through ultra-low (C+N) content, with appropriate Nb addition to ensure intergranular corrosion resistance via sensitization. Nippon Steel Corporation has previously developed high-purity ferritic stainless steel bar and wire rod for fine-diameter applications such as screws, bolts, welding materials, and wire mesh.[14]

On the other hand, for high-quality applications with strict quality requirements, such as automotive fuel system components, improvements in detection accuracy during ultrasonic flaw detection testing for internal material defects and in toughness are considered necessary. As described later, for high-purity ferritic stainless steel large-diameter bars and wire rods, coarse grain structure is thought to be the cause of challenges in ultrasonic flaw detection performance and toughness. The manufacturing of these components involves processes such as bar and wire rod forging, welding, and heat

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treatment,[15] necessitating the selection of appropriate utilization processing technologies that meet functional requirements like high strength, corrosion resistance, and magnetic properties. Furthermore, from an environmental impact reduction perspective, process simplification in these utilization processing technologies is also desirable.

This study reports on efforts to enhance quality (improved ultrasonic flaw detection performance, high toughness) and functionality (high strength, corrosion resistance, magnetic properties, etc.) in an integrated manufacturing process covering everything from bar and wire rod production to utilization processing technologies for high-purity ferritic stainless steel large-diameter bars and wire rods used in fuel system components.

2. High-quality Enhancement through Hot Rolled Microstructure Control of Large-diameter Bars and Wire Rods

2.1 Quality performance and microstructure of high-purity ferritic stainless steel large-diameter bars and wire rods

As mentioned earlier, improving the quality of steel materials involves enhancing detection accuracy in ultrasonic flaw detection tests, which detect internal defects, and improving toughness. **Figure 1** shows a schematic diagram of defects in bar steel. In addition to surface defects, steel may contain internal defects such as cavities and inclusions.[16,17] Industrially, internal defects are guaranteed by ultrasonic flaw detection.[18–20]

Figure 2 shows a schematic of internal defect detection via ultrasonic flaw detection. By applying a probe to the bar steel and injecting ultrasonic waves into the steel, internal defects cause the waves to reflect. This generates an internal defect signal (S), enabling the defect's location to be pinpointed. However, as described later, the presence of coarse-grained structures within the steel generates noise signals (N) unrelated to internal defects. This noise attenuates the ultrasonic waves, weakening the internal defect signal (S) and making its detection difficult. Therefore, improving the S/N ratio is essential for enhancing the accuracy of ultrasonic flaw detection.

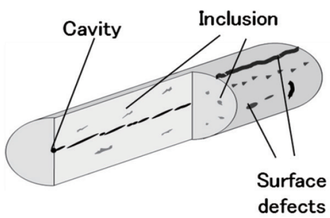

Fig. 1 Schematic diagram of defects in bar steel

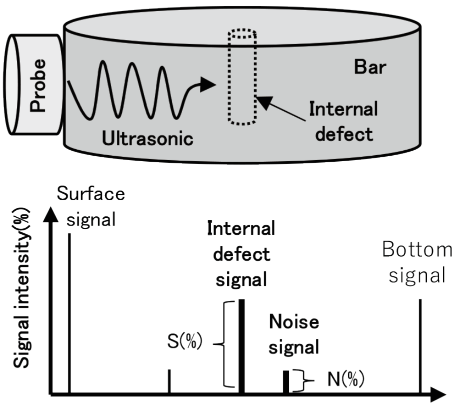

Fig. 2 Schematic diagram of internal defect detection by ultrasonic testing

Figure 3 shows the microstructure of NSSC180 large-diameter bar and wire rod. High-purity ferritic stainless steel large-diameter bars and wire rods may exhibit coarse-grained structures due to non-recrystallization, which can impair ultrasonic flaw detection performance.

Table 1 shows the representative chemical composition of NSSC180. In high-purity ferritic stainless steels, the ferrite former element Cr is high, and the stabilizing element Nb fixes the austenite former elements C and N. Consequently, the microstructure remains a single ferrite phase from solidification to room temperature. There is no transformation between ferrite (α) and austenite (γ), and the coarse grains formed during solidification are believed to remain.

The sound pressure P_x measured by ultrasonic flaw detection is composed of the initial sound pressure P_0, the arbitrary location x, and the attenuation coefficient α, as shown in Equation (1). It is considered that a larger attenuation coefficient results in a smaller sound pressure at the arbitrary location x.[21,22] Several expressions for the attenuation coefficient α have been proposed based on the relationship between the ultrasonic wavelength λ and the crystal grain size d.[21,22] According to Rayleigh scattering and Stochastic scattering in Equations (2) and (3), coarse grains are thought to increase the attenuation coefficient. This is believed to occur because the ultrasonic waves incident on the coarse grains scatter at the crystal grain boundaries, causing attenuation. According to the influence of grain size on the attenuation coefficient in ultrasonic flaw detection using ferritic steel and austenitic steel,[23] it has been experimentally confirmed that coarsening of grain size increases the attenuation coeffi-

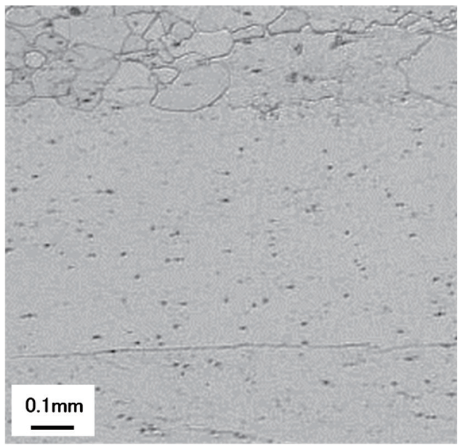

Fig. 3 Coarse-grained microstructure of high purity ferritic stainless steel large-diameter bar and wire rod NSSC180

Table 1 Typical chemical compositions of NSSC180

(mass%)

C	Si	Mn	Cr	Cu	Nb	N
0.01	0.30	0.3	19.1	0.3	0.5	0.01

cient and impairs ultrasonic flaw detection performance. Therefore, refining the grain size can be considered as an approach to improve the ultrasonic flaw detection performance of the material itself.

$$P_x = P_0 \cdot e^{-\alpha x} \quad (1)$$

When $\lambda >> d$ (Rayleigh scattering)

$$\alpha = Ad^3 \cdot f^4 \quad (2)$$

When $\lambda \approx d$ (Stochastic scattering)

$$\alpha = Bd \cdot f^2 \quad (3)$$

For large-diameter bars and wire rods, impacts are anticipated during handling, such as during secondary processing straightening,[24] making the assurance of steel toughness a challenge. According to conventional knowledge, the ductile-brittle transition temperature (DBTT) related to toughness exhibits grain size dependence, and it is known that coarser grains increase the DBTT and exhibit more brittle behavior.[25] This is thought to occur because the brittle fracture stress exhibits grain size dependence; coarse grains reduce the brittle fracture stress, and the material's yield stress exceeds this brittle fracture stress. Microstructure refinement is also considered an effective approach for enhancing steel toughness.

2.2 Approaches for microstructure refining

As discussed in the previous section, microstructure refinement is considered effective for improving the ultrasonic flaw detection performance and toughness of high-purity ferritic stainless steel large-diameter bars and wire rods. As mentioned earlier, high-purity ferritic stainless steel maintains a single-phase ferrite microstructure from solidification to room temperature without solid-state transformation. Therefore, refining the coarse grains formed during solidification through recrystallization during hot rolling is a viable approach. The $t_{0.5}$ (heat treatment time at which the recrystallization rate reaches 50%) for hot recrystallization of high-purity ferritic stainless steel is given by Equation (4).[26]

$$t_{0.5} = 8.4 \times 10^{-11} \cdot d_0^{\,1} \cdot \varepsilon^{-1.5} \cdot \dot{\varepsilon}^{-0.4} \cdot \exp\left(\frac{Q}{RT}\right) \quad (4)$$

where d_0: pre-processing grain size, ε: strain, $\dot{\varepsilon}$: strain rate, Q: activation energy for recrystallization, R: gas constant, T: temperature. Approaches to promote recrystallization include refining the initial grain size and increasing strain and strain rate. In 17Cr-based ferritic stainless steels exhibiting α/γ transformation, recovery, recrystallization, and deformed microstructure are observed from the high-temperature side of the hot rolling temperature range.[27] Therefore, determining the appropriate hot rolling temperature is also considered necessary to obtain a recrystallized microstructure.

Figure 4 shows the process at the stainless steel bar and wire rod plant at Yamaguchi Steel Works.[28] Typically, billets used for bar and wire rod rolling are produced with large cross-sections after casting, followed by block rolling. However, bar and wire rod plant at Yamaguchi Steel Works is characterized by performing direct bar and wire rod rolling after an inline block rolling process using an oblique rolling mill (High Reduction Mill) and a holding furnace. oblique rolling enables the application of both compressive and shear deformation. The shear deformation effect allows for high strain processing of the steel.[28, 29] Optimizing the hot rolling conditions, including high strain processing via oblique rolling, is expected to promote recrystallization in high-purity ferritic stainless steel bars and wire rods.

The effect of thermal history on the recrystallization behavior of high-purity ferritic stainless steel bar and wire rod NSSC180 was investigated. For an equiaxed microstructure with an initial grain size of approximately 1 mm, a thermal history as shown in **Fig. 5** was used as the basic condition. Strain, strain rate, temperature, and annealing time were varied, and the average grain size in the compression direction at the center of the steel was measured.

Figure 6 shows the effect of the thermal history on the average grain size of the high-purity ferritic stainless steel bar and wire rod NSSC180. The average grain size exhibits a minimum value relative to the test temperature, with a tendency toward coarse grains on both the high-temperature and low-temperature sides of this minimum. On the high-temperature side, this is thought to result from early completion of recrystallization followed by grain growth, leading to coarse grains. On the low-temperature side, it is thought to result from the presence of coarse unrecrystallized grains, leading to coarse grains. Increasing strain promotes fine grain formation in all test temperature ranges. This is thought to occur because increased strain elevates strain and strain rate in the specimen center, accumulating strain energy that drives recrystallization. This accumulation increases recrystallization nuclei, leading to fine grain formation. Results from small-piece hot forming tests suggest that increasing strain and strain rate, along with selecting an appropriate processing temperature, are effective for achieving fine grain.

Since large strain processing at an appropriate processing temperature is effective for grain refinement, the influence of the processing rate of oblique rolling on the microstructure was investigated using a three-roll oblique rolling mill.[30, 31] For NSSC180 round bar specimens with an equiaxed microstructure and an initial grain size of approximately 1 mm, the heating and processing tempera-

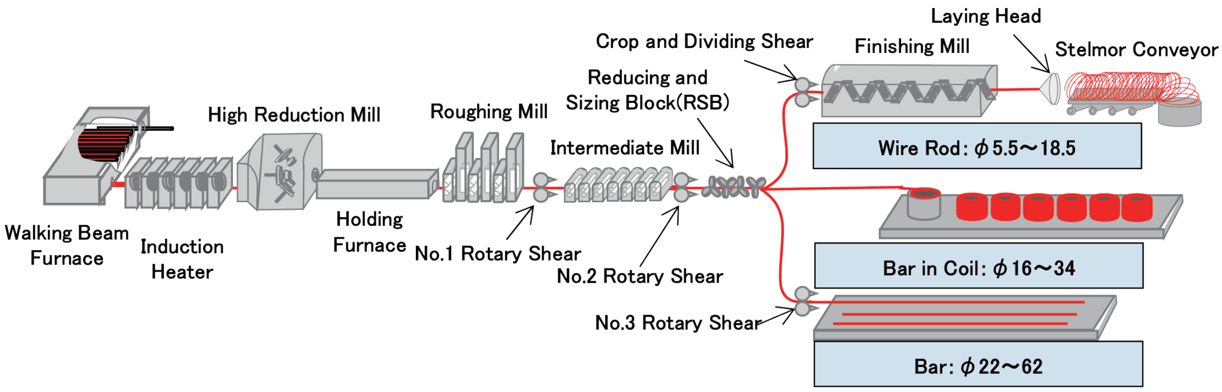

Fig. 4 Processes at the stainless steel bar and wire rod plant at Yamaguchi Steel Works[28]

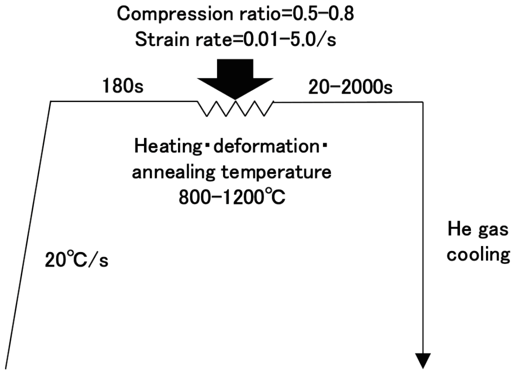

Fig. 5 Thermal history conditions

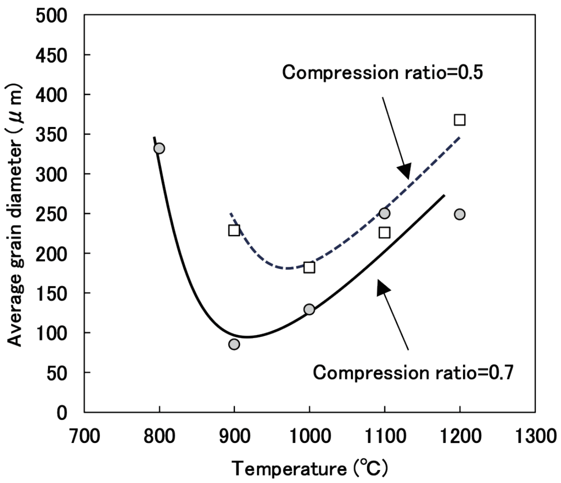

Fig. 6 Effect of thermal history on the average grain size of NSSC180 high purity ferritic stainless steel bar and wire rod

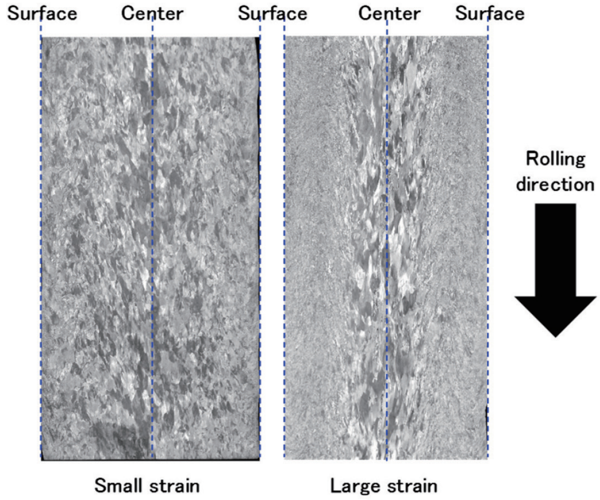

Fig. 7 Effect of gradient rolling work rate on the microstructure of high purity ferritic stainless steel bar and wire rod NSSC180

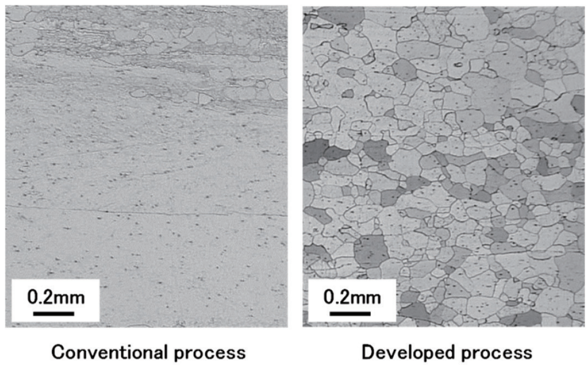

Fig. 8 Microstructure of conventional and hot rolled microstructure control materials of NSSC180 large-diameter bar and wire rod

tures were fixed. The processing rate of the oblique rolling was varied at two levels (low processing rate, high processing rate) using a three-roll oblique rolling mill. After processing, the specimens were water-quenched. The central longitudinal section of the specimens was polished and etched for microstructural observation.

Figure 7 shows the effect of oblique rolling reduction ratio on the microstructure of high-purity ferritic stainless steel bar and wire rod NSSC180. The surface layer of the steel after oblique rolling exhibits a recrystallized microstructure with a finer grain tendency compared to the core. This is attributed to the fact that oblique rolling induces both compressive and shear deformation in the surface layer, promoting recrystallization due to large strain. As the oblique rolling ratio increases, the region subjected to compressive and shear deformation extends toward the core of the steel, promoting recrystallization and grain refinement even in the core. By optimizing oblique rolling conditions to promote recrystallization before rough rolling and refine the average grain size, subsequent recrystallization after rough rolling is facilitated, enabling grain refinement in large-diameter bars and wire rods.

2.3 Microstructure and quality performance of hot rolled microstructure control material

Based on the aforementioned findings, high-purity ferritic stainless steel large-diameter bars and wire rods were produced under optimized hot-rolling conditions. **Figure 8** shows the microstructures of the conventional material and the hot rolled microstructure control material for NSSC180 large-diameter bars and wire rods. The conventional material exhibits coarse grains due to the unrecrystallized structure, whereas the hot rolled microstructure control material displays a recrystallized structure with fine-grained microstructure.

To confirm the effect of high quality on the fine-grained hot rolled microstructure control large-diameter bar and wire rod, its ultrasonic flaw detection performance and toughness were evaluated. For ultrasonic flaw detection performance, the test specimens were prepared by drilling artificial defects toward the center of the large-diameter bar and wire rod along the rolling direction. Using a GE portable phased array ultrasonic flaw detector (5 MHz, direct contact, vertical testing), the S/N ratio (dB) of the artificial defect signal (S) to noise signal (N) in the test specimens was investigated to evaluate ultrasonic flaw detection performance. **Figure 9** shows the ultrasonic flaw detection performance of the NSSC180 large-diameter bar and wire rod specimens for the conventional material and the hot rolled microstructure control material. The S/N ratio of the hot rolled microstructure control material was more than twice that of the conventional material (approximately 5 dB improvement). A reduction in noise signals and an increase in artificial defect signals were observed, with the artificial defect signals being clear, indicating an improvement in ultrasonic flaw detection performance. This is thought to be due to the fine-grained structure of the hot rolled microstructure control material, which suppresses ultrasonic scattering and attenuation, leading to an improved S/N ratio.

Regarding toughness, Charpy impact test specimens (full size, U-notch) were cut from the large-diameter bar and wire rod and the impact values were measured. The specimens were machined so that the steel's radial direction aligned with the notch bottom direction. Furthermore, the test temperature was standardized as the differential temperature between the test temperature and the ductile-brittle transition temperature of the conventional material. **Figure 10** shows the toughness of the conventional material and the hot rolled microstructure control material for NSSC180 large-diameter bar and wire rod. The transition temperature of the hot rolled microstructure control material is 100°C lower than that of the conventional material, with a narrower temperature range near the transition temperature, indicating superior toughness. The fine-grained structure of the hot rolled microstructure control material increases its brittle fracture stress compared to the conventional material and facilitates plastic deformation. Consequently, the toughness of the hot rolled microstructure control is considered to be improved.

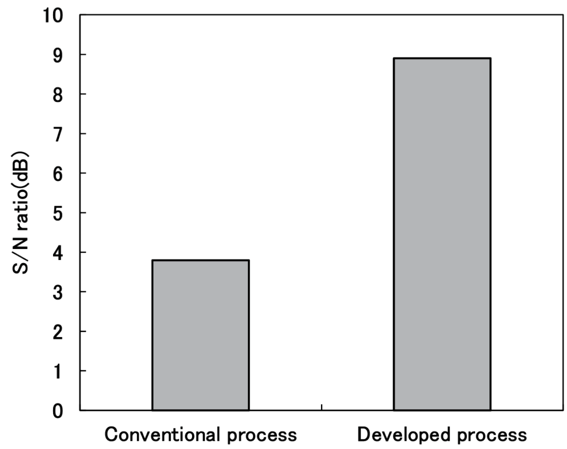

Fig. 9 Ultrasonic flaw detection performance of conventional and hot rolled microstructure control materials in NSSC180 large-diameter bar and wire rod

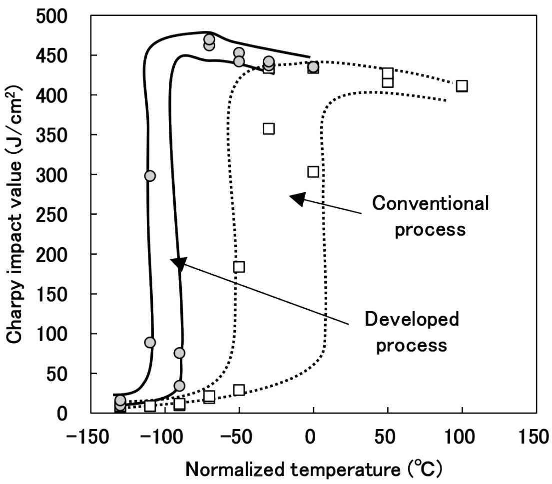

Fig. 10 Toughness of conventional and hot rolled microstructure control materials of NSSC180 large-diameter bar and wire rod

Therefore, hot rolled microstructure control of high-purity ferritic stainless steel large-diameter bar and wire rod results in microstructure refinement, improving ultrasonic flaw detection performance and toughness compared to conventional material, and is expected to enhance the quality of large-diameter bar and wire rod.

3. Functional Enhancement through Utilization Processing Technologies

Manufacturing fuel system components such as high-pressure fuel pumps and injectors involves processes like forging, welding, and heat treatment of the bar and wire rod. Selecting appropriate utilization processing technologies tailored to each required function (high strength, corrosion resistance, magnetic properties, etc.) is desirable. This chapter describes the fundamental properties of high-purity ferritic stainless steel bar and wire rod and the utilization processing technologies for high-strength and soft magnetic applications.

3.1 Basic properties of high-purity ferritic stainless steel bars and wire rods

Table 2 shows the salt spray test evaluation results for various stainless steel bars and wire rods.[32] It shows the rusting condition after salt spray testing on #500 surface ground finishes of various wire materials. The NSSC180 bar and wire rod exhibits significantly superior performance compared to Type 430, demonstrating corrosion resistance characteristics close to Type 304. Furthermore, ferritic stainless steels are considered advantageous regarding stress corrosion cracking resistance, which is problematic in austenitic stainless steels like Type 304.[33]

Fuel components often require joining with other parts after forming. Joining is typically performed via bolting, MIG/TIG welding, or laser welding. For automotive components, the mating part is frequently a high-carbon martensitic stainless steel part. In welding, issues such as sensitization due to carbon influx into the ferritic stainless steel can degrade joint quality, requiring careful attention.

The corrosion condition after improved Strauss testing was investigated for samples of 0.6%C high-carbon martensitic stainless steel welded to NSSC180 and Type 430L (Ultra-lowC) using fiber laser welding. **Figure 11** shows the effect of laser welding speed on the corrosion resistance of Type 430L and NSSC180.[32] At the high welding speed of 4 m/min, no intergranular corrosion occurred at the joint for either material. However, at slower speeds of 2 m/min and 1 m/min, intergranular corrosion was observed at the joint in Type 430L. In contrast, no intergranular corrosion was observed at the joints of NSSC180. At high welding speeds, the heat input is low, and the laser welded area is rapidly cooled, making sensitiza-

Table 2 Salt spray test evaluation of various types of stainless steel bar and wire rod[32]

	Superior ← Rust level → Inferior					
	A	B	C	D	E	F
NSSC180	■	■				
Type430			■	■	■	
Type304	■	■				

Salt spray test:5%NaCl, 35℃, 1000hr

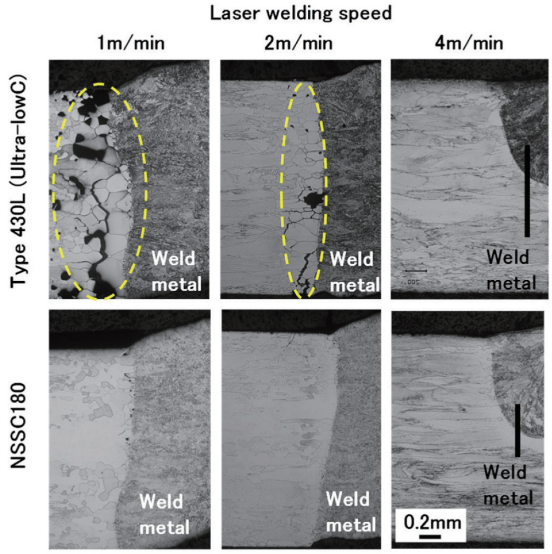

Fig. 11 Effect of laser welding speed on the corrosion resistance of Type 430L and NSSC180[32)]

tion less likely. However, as the welding speed decreases, the heat input increases. It is considered that sensitization occurs in Type 430L, which lacks Nb addition, leading to intergranular corrosion. NSSC180 can be joined over a wide range of laser welding speeds and is considered to exhibit excellent post-weld resistance to intergranular corrosion, making it effective for improving the overall durability of components.

3.2 Processing technologies for high-strength and soft-magnetic applications

To enhance the reliability of fuel system components under high fuel pressure conditions, forging techniques that integrate components and increase strength by reducing welded areas are considered. Forging offers superior material yield compared to machining and is effective for near-net-shape forming. However, forging temperature significantly influences deformation resistance, material strength, dimensional accuracy, and contributes to die life load, necessitating appropriate temperature selection. Therefore, the effect of compression temperature on the compressive deformation resistance of high-purity ferritic stainless steel NSSC180 was investigated. For NSSC180 bar and wire rod, after heating using a hot forming press from RT to 1 100°C, compressive deformation resistance was measured at 10/s, and the HV hardness at the center of the steel after the compression test was examined.

Figure 12 shows the effect of compression temperature on the compression deformation resistance of NSSC180 bar and wire rod.[32)] At 600°C warm compression, deformatioen resistance is approximately half that at room temperature, and at 1 000°C hot compression, it is about one-tenth of the room temperature value. This is expected to contribute to the formability of complex-shaped components during warm-hot forging. Furthermore, the HV hardness after warm compression at 600°C is around 260, which is higher than the HV hardness of solution-treated material (approximately 160). It is presumed that warm compression suppresses recovery and increases work hardening, leading to an increase in dislocation density and higher hardness. Strength enhancement through the application of warm compression is therefore anticipated.

Next, in the magnetic circuit region of injectors, the material

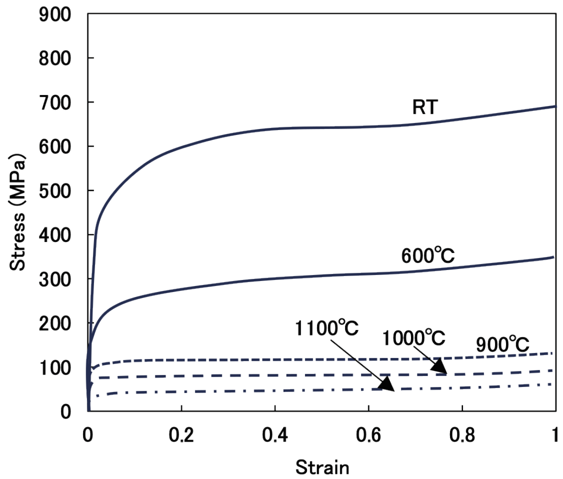

Fig. 12 Effect of compressive temperature on the compressive deformation resistance of NSSC180 bar and wire rod[32)]

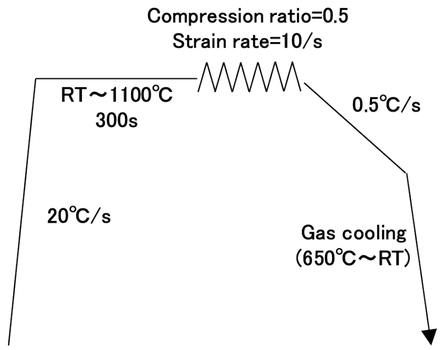

Fig. 13 Warm compression process history

must be soft magnetic, and magnetically annealed electromagnetic stainless steel is primarily used. Magnetic annealing is a high-temperature, long-duration vacuum heat treatment that improves soft-magnetic properties by reducing steel strain and coarsening grain size. While injector components are often manufactured via machining or cold forging, utilizing heat during hot forging to reduce strain may eliminate the need for magnetic annealing. This study investigated the effect of warm-hot compression on the soft-magnetic properties of high-purity ferritic stainless steel bar and wire rod NSSC180. **Figure 13** shows the warm-hot compression processing history. Test specimens φ12 × 20 mm were cut from NSSC180 bar and wire rod. Using a hot forming press, the specimens were heated from RT to 1 100°C for 300 s, then compressed at strain = 0.5, a strain rate of 10/s, followed by cooling equivalent to 0.5°C/s to 650°C, and then gas quenching from 650°C to RT. From the compressed specimen, a ring specimen with an outer diameter of φ13 mm, inner diameter of φ8 mm, and height of 5 mm was machined, and its soft-magnetic properties (magnetic flux density and coercive force) were evaluated. For comparison, a high-purity ferritic stainless steel bar and wire rod that had undergone magnetic annealing at 950°C for 2 hours was also evaluated.

Figures 14 and **15** show the effect of thermal history on the magnetic flux density and coercive force of the NSSC180 bar and wire rod. B_{10} and B_{100} represent the magnetic flux density (T) at 10

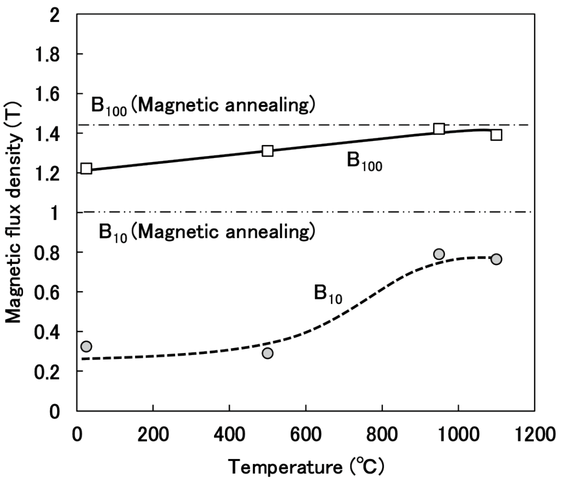

Fig. 14 Effect of thermal history on the magnetic flux density of NSSC180 bar and wire rod

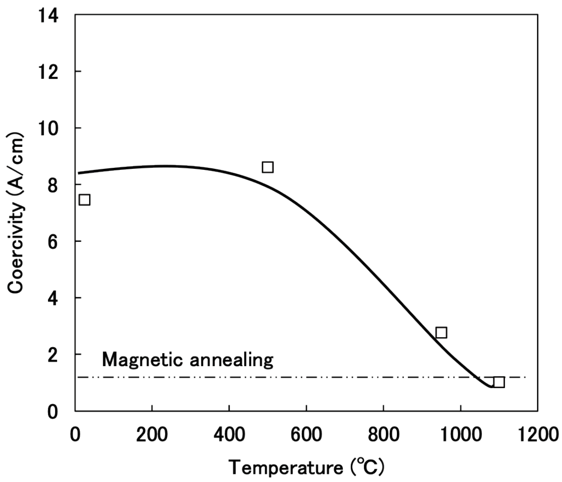

Fig. 15 Effect of thermal history on the coercive force of NSSC180 bar and wire rod

Oe and 100 Oe, respectively; higher values indicate greater output and are preferable. Coercivity is the opposing external magnetic field required to demagnetize the steel. A lower coercivity indicates better responsiveness and is desirable for soft magnetic materials. The B_{10} and B_{100} values for room-temperature compression (cold compression) are approximately 0.3 and 1.25, respectively, which are lower than those for magnetically annealed material. This is thought to be due to residual strain from cold deformation. When cooled slowly after hot compression near 1 100°C, the magnetic flux density increases compared to room-temperature compression, with B_{100} improving to nearly 1.4, approaching magnetic annealed material. This is thought to result from coarse grain formation during high-temperature heat treatment, combined with the recovery of compression-induced strain during slow cooling after compression. Regarding coercive force, cold compression yields a high value of approximately 8, but compression at 1 100°C reduces it to about 1, exhibiting soft-magnetic properties comparable to magnetic annealing. This suggests the potential for omitting the magnetic annealing process.

Therefore, high-purity ferritic stainless steel bar and wire rod NSSC180 offers excellent corrosion resistance at welded joints. When formed at an appropriate forging temperature, it exhibits high strength and superior soft-magnetic properties, making it suitable for high-performance fuel system components.

4. Conclusion

Against the backdrop of increasing gasoline engine efficiency, this study investigated quality improvement and functional enhancement of large-diameter bar and wire rod of high-purity ferritic stainless steel NSSC180, suitable for high-pressure fuel pumps and injectors—key components in direct-injection gasoline engines. Since coarse grain structure impedes ultrasonic flaw detection performance, recrystallization was promoted through large strain processing using an oblique rolling mill, resulting in grain refinement. As a result, ultrasonic flaw detection tests showed that the S/N ratio of the hot rolled microstructure control material was more than twice that of the conventional material, indicating improved ultrasonic flaw detection performance. Enhanced toughness was also observed, suggesting a contribution to achieving higher quality. Furthermore, appropriate utilization processing technologies, such as laser welding and forging temperatures, enabled the achievement of excellent corrosion resistance, high strength, and superior soft-magnetic properties without magnetic annealing. This is expected to enhance the functionality of fuel system components and reduce environmental impact. The demand for improved reliability, enhanced functionality, and process simplification in automotive components is expected to continue growing, encompassing the entire manufacturing process from bar and wire rod production to utilization processing technologies. Based on the findings of this research, development activities will continue to optimize steel materials and the integrated manufacturing process.

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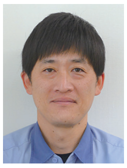

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