NIPPON STEEL TECHNICAL REPORT No. 135 MARCH 2026

Technical Report

Development of Bainitic Wire Rod (Multi Free Wire Rod) for Non-heat-treatment Bolt

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Abstract

In order to achieve carbon neutrality in the bolt manufacturing process, elimination of the bluing process is required for non-heat-treatment bolts. Newly developed steel for non-heat-treatment bolts (Multi Free (MF) wire rod) characterized bainitic microstructure by an online controlled cooling process. Non-heat-treatment bolts made from MF wire rod satisfied the properties of JIS 8.8 class. The complete elimination of heat treatment in the bolt manufacturing process was achieved by the MF wire rod.

1. Introduction

Steel bolts are essential industrial components used in an extremely wide range of applications, including transportation equipment such as automobiles, electrical equipment, shipbuilding, bridges, and housing. There is a strong demand for reducing greenhouse gas emissions, including CO_2, in their LCA. Nippon Steel Corporation is undertaking various initiatives from the perspectives of "weight reduction and CO_2 emission reduction in LCA," "cost reduction," and "optimal mass production systems." One such initiative is Eco-Products™, a high-performance steel that contributes to carbon neutrality during part manufacturing and in final product use. **Figure 1** illustrates a typical automotive bolt manufacturing process. Wire rod produced by hot rolling undergoes wire drawing and spheroidization annealing (SA) at the wire manufacturer. At the bolt manufacturer, it is shaped into a bolt form through cold forging and rolling. Subsequently, it undergoes quenching and tempering (heat treatment), plating, and baking to remove hydrogen absorbed during plating. Annealing and quenching and tempering consume large amounts of energy during heating and emit significant CO_2. Therefore, non-heat-treatment bolt wire has been developed to reduce CO_2 emissions in the bolt manufacturing process.[1, 2] Non-heat-treatment bolts utilize work hardening during the wire drawing process instead of quenching and tempering to impart strength corresponding to the bolt's strength class. Using wire rod for non-heat-treatment bolts enables the elimination of spheroidizing annealing before cold forging and the quenching and tempering process. It also allows the elimination of the straightening process after quenching and tempering for long bolts. However, conventional wire rod for non-heat-treatment bolts had the following issues:

(1) Addition of a bluing process

While JIS standards[3] for bolts specify yield strength and permanent elongation, conventional non-heat-treatment bolts have low yield strength and high permanent elongation, necessitating the addition of a bluing process[4] in the final stage. As a result, conventional non-heat-treatment bolts could not completely eliminate heat treatment.

(2) Reduced cold forgeability

Wire drawing before cold forging imparts the necessary strength to the bolt, resulting in high material strength during cold forging. This places significant stress on the dies and the steel, raising concerns about reduced die life and the occurrence of cracks in the steel during cold forging.

(3) Concerns about reduced underhead fillet ductility and delayed fracture

Non-heat-treatment bolts become final products without undergoing quenching and tempering after cold forging. Consequently, the strain distribution from cold forging persists in the final product, resulting in a hard distribution within the bolt. Particularly at the underhead fillet, even when the threaded portion conforms to strength class 8.8, this area may exhibit strength equivalent to class 12.9, depending on the bolt geometry. This raises concerns about reduced underhead fillet ductility and potential delayed fracture[5] during service.

To overcome these challenges, Nippon Steel has developed a new non-tempered wire rod for bolts (MF wire rod: Multi Free) that completely eliminates heat treatment from the manufacturing process for JIS strength class 8.8 bolts while satisfying the necessary

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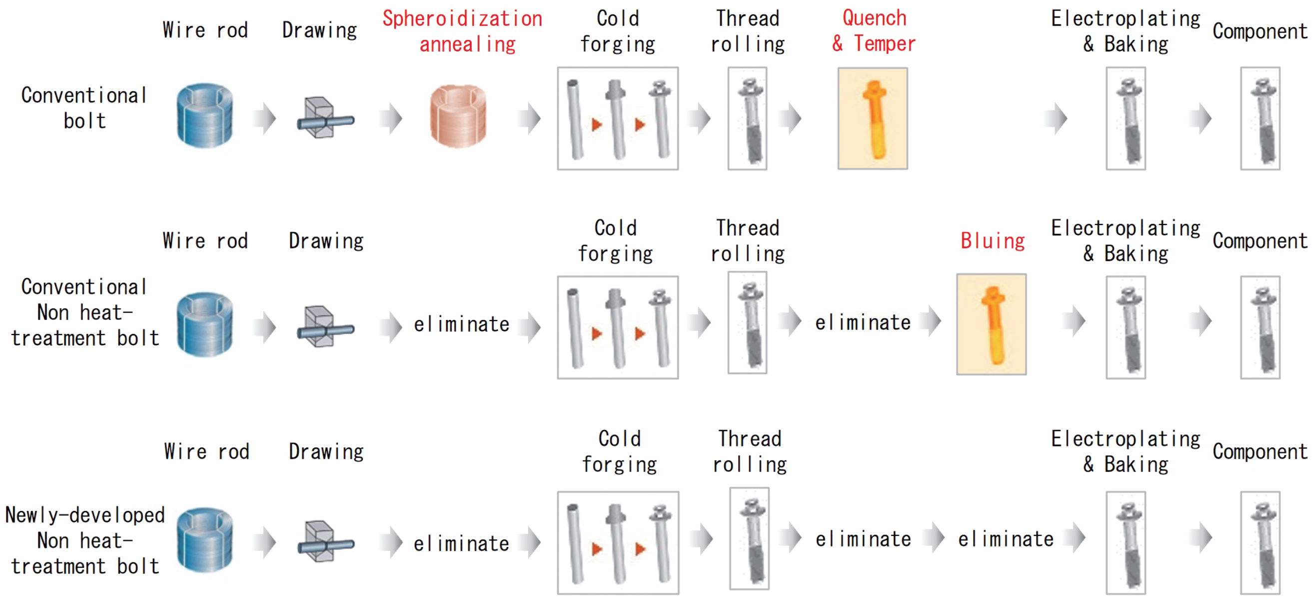


Fig. 1 Manufacturing process of automotive bolts

properties for the bolts. This paper presents the development concept of MF wire rod and evaluates its properties both as wire rod and as bolts. Applying this developed steel enables CO_2 emissions reduction in the bolt manufacturing process compared to conventional quenched and tempered bolts: 139 kg-CO_2/ton-steel from eliminating spheroidizing annealing and 250 kg-CO_2/ton-steel from eliminating quenching and tempering.

2. Development Concept of MF Wire Rod

To address the challenges of conventional non-heat-treatment bolts, we decided to utilize bainite microstructure. Bainite microstructure has a fine substructure,[6] which allows a high yield ratio (yield strength/tensile strength). Therefore, the bolt properties can be achieved solely through baking after plating, without the bluing process conventionally required for non-heat-treatment bolts, making complete elimination of heat treatment possible.

Wire rod for non-heat-treatment bolts requires excellent cold forgeability, as bolts are formed by cold forging wire rod with tensile strength of 800–900 MPa obtained through wire drawing. Achieving a fine and homogeneous microstructure enables the cold forgeability required for non-heat-treatment bolts. The bainite microstructure, characterized by fine cementite dispersed in a ferrite matrix, offers an excellent balance of strength and ductility.[7] This bainite structure reduces the risk of cracking during cold forging of complex bolt head shapes. Furthermore, bainite microstructures have a lower strain hardening rate than ferrite-pearlite microstructures.[8] The Bauschinger effect,[2, 9] which facilitates deformation in the compression direction during cold forging due to tensile strain from wire drawing, further reduces flow stress and helps suppress die wear.

The microstructure of non-heat-treatment bolts elongates longitudinally during wire drawing. Structures that are elongated parallel to the stress direction are known to exhibit superior resistance to delayed fracture.[10, 11] Thus, incorporating a uniform bainite structure into an elongated microstructure via wire drawing is expected to yield excellent resistance to delayed fracture.

To achieve a uniform bainite microstructure, isothermal heat treatment is necessary, which involves holding the austenite at a constant temperature to induce transformation. Conventionally, offline lead bath heat treatment is applied to wire rod after rolling, but this adds an intermediate heat treatment step, preventing complete elimination of heat treatment and raising environmental and productivity concerns. Nippon Steel addressed this by enabling uniform bainite formation at the wire rod stage using online conditioning and cooling equipment directly connected to the rolling line, allowing CO_2 emission reduction and high productivity.[12, 13]

3. Characteristics of MF Wire Rod

3.1 Manufacturing method

MF wire rod uses boron steel conforming to SAE (Society of Automotive Engineers) standards, with chemical composition shown in **Table 1**. After hot rolling, controlled cooling is performed using an online controlled cooling system installed downstream of the rolling line to obtain a homogeneous bainite microstructure. The tensile strength of bainite microstructure varies significantly with transformation temperature.[14, 15] Temperature control in the online controlled cooling system is therefore critical in determining the properties of MF wire rod. By combining steel transformation characteristics with precise temperature control, a homogeneous microstructure is achieved.

Table 1 Chemical composition of MF wire rod (mass%)

	C	Si	Mn	P	S	B	SAE standard
10B21-MF	0.18/0.23	0.15/0.35	0.60/0.90	≤0.0030	≤0.0030	0.0005/0.0030	SAE 10B21
15B23-MF	0.19/0.25	0.15/0.35	1.35/1.65	≤0.0030	≤0.0030	0.0005/0.0030	SAE 15B23

3.2 Microstructure and mechanical properties

Photo 1 shows the microstructure of the test steel. Controlled cooling yields a uniform bainite structure with finely dispersed cementite throughout the wire, from the surface to the core. **Figure 2** presents hardness measurement results from the surface to the core within a cross-section of $\varphi10$ wire, demonstrating nearly constant hardness from surface to core. **Figure 3** shows the strength variation along the entire length of one coil (2 tons) of wire rod. Temperature control during cooling enables production of wire rod with extremely low tensile strength variation from coil head to tail.

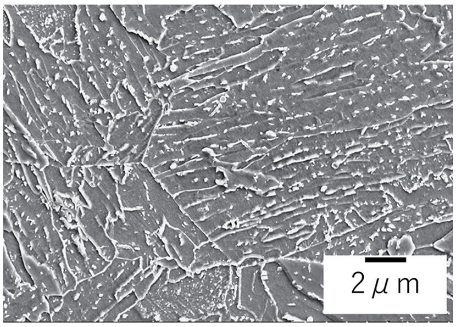


Photo 1 Microstructure of MF wire rod

3.3 Cold forgeability

Drawing was performed on MF wire rod manufactured using online controlled cooling equipment. The resulting drawn wire was used to evaluate cold forging properties for bolts. Since the strain during bolt head forming is approximately equivalent strain 1.5,[3] flow stress at equivalent strain 1.5 (compression ratio approx. 78%) was measured.[16]

As shown in **Fig. 4**, flow stress of the MF wire rod at equivalent strain 1.5 (compression rate approx. 78%) is equivalent to that of spheroidized annealed S45C (S45C-SA), used for quenched and tempered bolts. Despite the high tensile strength of the drawn wire, MF wire rod exhibits excellent forgeability, attributed to the low work hardening rate of bainite and the Bauschinger effect.

Crack susceptibility of MF wire rod was evaluated by the limit compression ratio—the maximum compression ratio at which no cracking occurs in a cold upset test[17] on notched cylindrical specimens cut from the wire. As shown in **Fig. 5**, MF wire rod exhibits a higher limit of upset ratio than S45C-SA, indicating lower crack susceptibility.

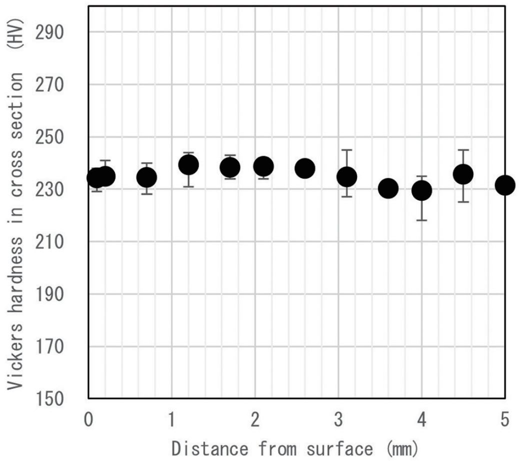


Fig. 2 Vickers hardness in cross section

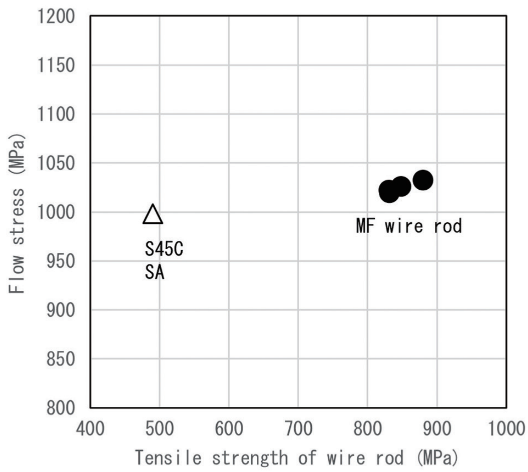


Fig. 4 Relationship between tensile strength and flow stress

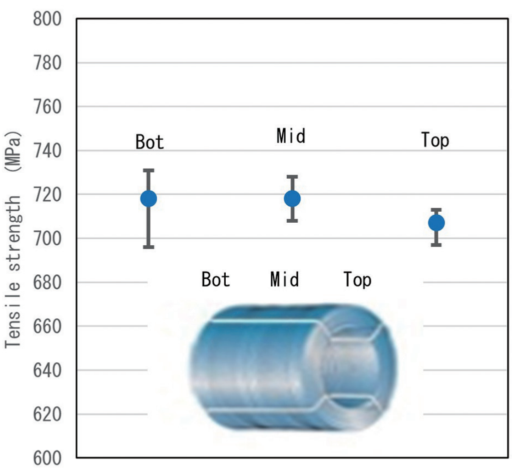


Fig. 3 Tensile strength in coils

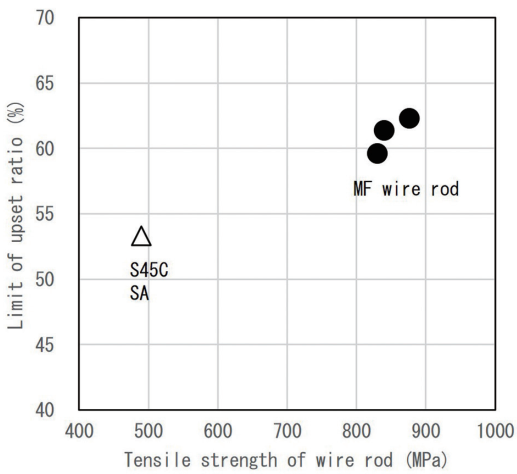


Fig. 5 Relationship between tensile strength and limit of upset ratio

Bolt forging experiments using a multi-stage forming machine produced JIS M8 flange bolts (**Fig. 6**). Bolts were successfully formed into the specified shape, with no damage observed on forging dies or bolts, confirming process feasibility. To assess forgeability of MF wire rod, the forging limit of the flange section was investigated by adjusting insertion depth during bolt forging. As shown in **Fig. 7**, even under severe conditions where cracking occurs in the flange section of S45C-SA, conventionally used as a quenched and tempered bolt, no cracking occurred with MF wire rod. This indicates that MF wire rod can be applied to complex or severely shaped components.

4. Properties of Bolts Made from MF Wire Rod

4.1 Evaluation method

M8 flange bolts were evaluated according to JIS B 1051:2014. Properties of as-forged bolts, baked bolts, and blued bolts were compared to verify the possibility of eliminating heat treatment by skipping the bluing process.

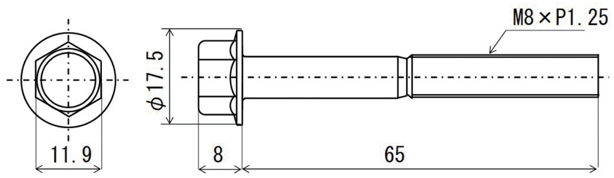


Fig. 6 Shape and dimensions in mm of bolts used in this study

4.2 Mechanical properties of bolts

Test specimens conforming to JIS 14A were cut from bolts and subjected to tensile testing. The tensile test results are shown in **Table 2**. Both baked and blued bolts satisfied specifications class 8.8. The baked bolts exhibited properties equivalent to those of the blued bolts. As shown in **Fig. 8**, the yield ratio of bolts made from MF wire rod was approximately 0.8 for as-forged bolts. However, applying either baking or bluing treatment resulted in a yield ratio of 0.9 or higher.

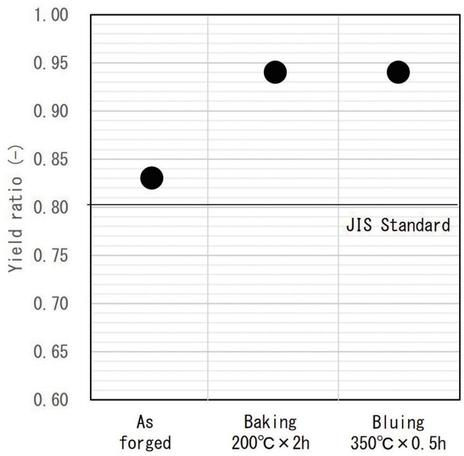


Fig. 8 Yield ratio of non-heat treatment bolt

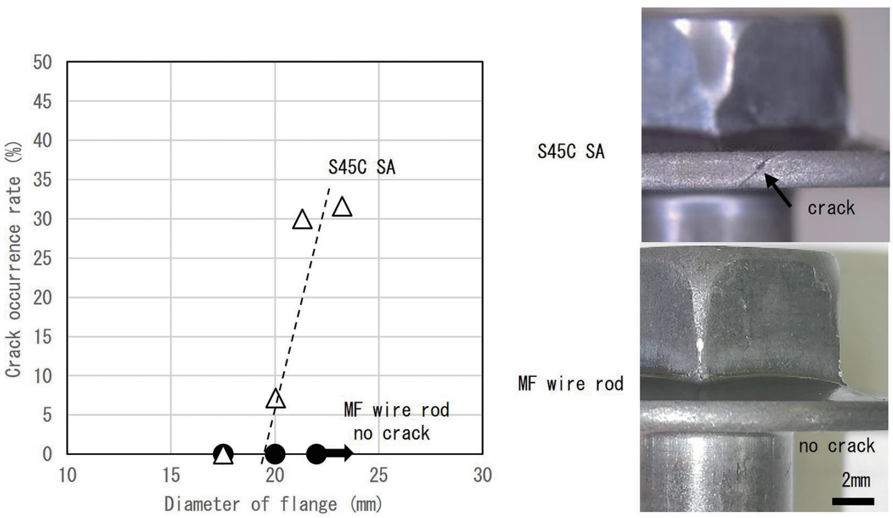


Fig. 7 Limit of cold heading of flange in bolt

Table 2 Mechanical properties of 8.8 class non-heat-treated bolt

	Aging conditions	TS (MPa)	0.2%PS (MPa)	YP/TS	El/5d (%)	RA (%)	Hardness (HV)
MF wire rod	None (As forged)	837	697	0.83	16.0	73.1	253
	Baking 200°C×2h	896	847	0.94	14.0	70.0	271
	Bluing 350°C×0.5h	890	834	0.94	16.3	70.3	270
JIS standard Grade 8.8		min. 800	min. 640	min. 0.8	min. 12	min. 48	250–320

4.3 Wedge tensile test

A wedge tensile test was conducted under the conditions shown in **Fig. 9**, with results in **Fig. 10**. All bolts—as-forged, baked, and blued—fractured normally at the threaded section, not at the underhead fillet. The tensile strength matched results obtained at 0° without a wedge. This indicates that bolts made from MF wire rod possess sufficient underhead fillet ductility.

4.4 Proof load test

Results are shown in **Fig. 11**. Permanent elongation must be within ±12.5 μm, including measurement error. No permanent elongation occurred in the bolts made from MF wire rod, whether baked or blued.

Based on the above, bolts made from MF wire rod satisfy the characteristics of JIS-specified strength class 8.8 bolts with only baking after plating. This eliminates the need for the bluing process required in conventional non-heat-treatment bolt manufacturing processes, enabling the complete elimination of heat treatment—a feat unachievable with conventional non-heat-treatment bolt wire.

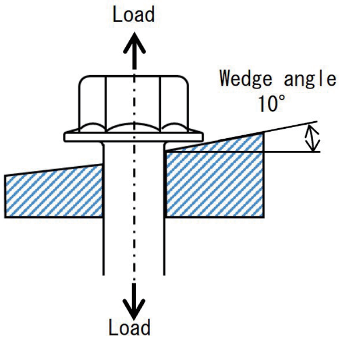


Fig. 9 Schematic illustrations of wedge loading test

4.5 Delayed fracture resistance

Delayed fracture resistance was evaluated using SSRT (Slow Strain Rate Tensile Test) on M8 flange bolts. Bolts were subjected to cathodic hydrogen charging and then zinc plated to prevent hydrogen release during testing, then left at room temperature to homogenize hydrogen concentration before SSRT. SSRT results are shown in **Table 3**, and the fracture surface is shown in **Photo 2**. The non-heat-treatment bolt of strength class 8.8 did not fracture from the underhead fillet, but instead fractured from the threaded section, exhibiting a ductile fracture surface. Quenched and tempered bolts made from boron steel 10B21 or low-alloy steel SCM435 fractured before reaching maximum load when adjusted to strength class 12.9, exhibiting intergranular fracture surfaces. Therefore, non-heat-treatment bolts using MF wire rod possess sufficient delayed fracture resistance for practical use.

5. Conclusion

To reduce CO_2 emissions in automotive component manufacturing, we developed MF wire rod (Multi Free) for fully heat-treatment-free non-heat-treatment bolts utilizing bainite microstructure. This developed steel enables CO_2 emission reduction and heat treatment cost savings by eliminating (Free) multiple heat treatment processes (annealing, offline isothermal transformation treatment,

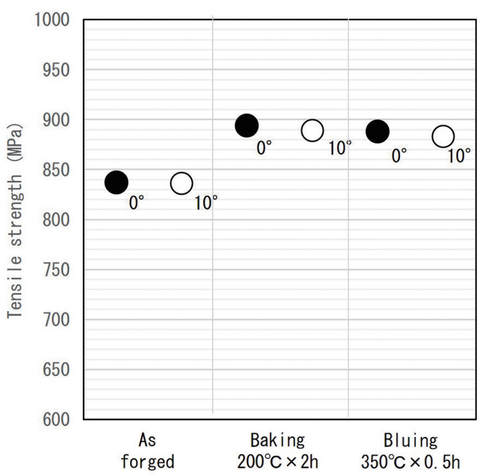


Fig. 10 Tensile strength under wedge loading

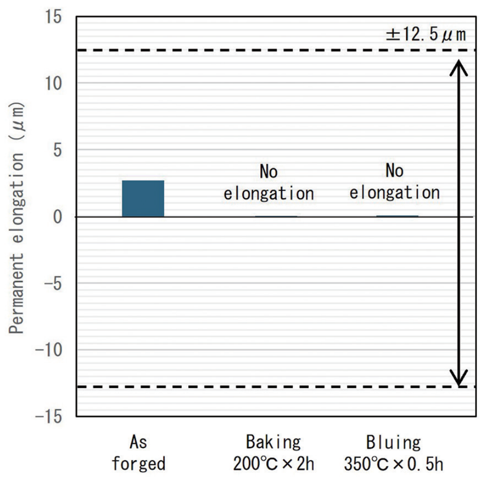
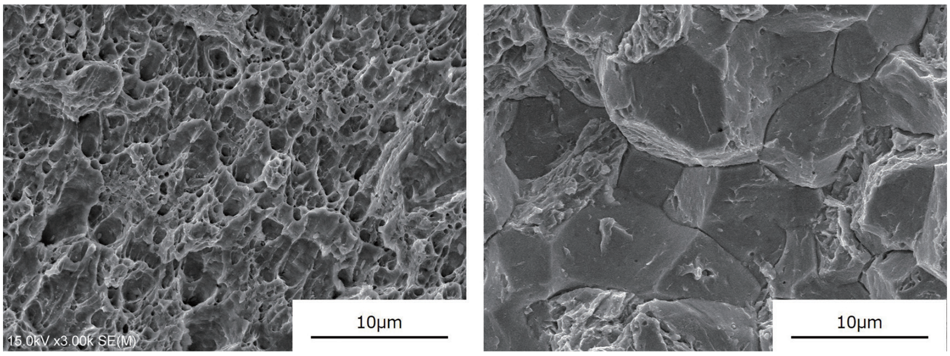


Fig. 11 Results of proof load test

Table 3 Result of SSRT

	Steel	Grade	Result	Break point	Fracture surface
Non-heat-treatment bolt	MF wire rod	8.8	Good	Screw part	Ductile fracture
Conventional heat-treatment bolt	Boron steel 10B21	8.8	Good	Screw part	Ductile fracture
		10.9	Good	Screw part	Ductile fracture
	Low alloy steel SCM435	10.9	Good	Screw part	Ductile fracture
		12.9	Bad	Screw part	Intergranular fracture



(a) MF wire rod (b) SCM435 grade12.9

Photo 2 SEM micrograph of fracture surface

quenching and tempering, bluing) in the bolt manufacturing process using online controlled cooling equipment. Furthermore, since no bolt bending occurs during quenching, eliminating (Free) inspection and straightening of long bolts. Furthermore, it eliminates the need for bolt manufacturers to replace aging heat treatment equipment or perform maintenance and reduces outsourced heat treatment costs.

Excellent forgeability enables shapes previously difficult with non-heat-treatment bolts, potentially increasing bolt design freedom (Free). Achieving multiple “Frees” led to the name Multi Free wire rod (MF wire rod). MF wire rod is increasingly adopted across various fields, including automotive bolts, electrical appliances, and construction applications. It is a product that enables carbon neutrality, cost reduction, and production system optimization in bolt manufacturing processes.

Furthermore, increased bolt strength enables, for example, lightweighting of automobile bodies, thereby contributing to the reduction of CO_2 emissions generated during vehicle operation. For this reason, Nippon Steel is advancing development of high-strength MF wire rod that simultaneously achieves high bolt strength, cold forgeability, and resistance to delayed fracture.

References

1) Serikawa, O.: Netsu Shori. 24, 25 (1984)
2) Kanisawa, H. et al.: Journal of the Japan Institute of Metals. 30 (6), 557 (1991)
3) JIS B 1051 Mechanical Properties of Fasteners Made of Carbon Steel and Alloy Steel. 2014
4) Sunami, E. et al.: Proceedings of the 104th Annual Meeting of the Iron and Steel Institute of Japan. 68 (12), S1282 (1982)
5) Matsuyama, S.: Delayed Fracture. Nikkan Kogyo Shimbun, 1989
6) Takayama, N. et al.: Acta. Mater. 60, 2387 (2012)
7) Ochiai, I. et al.: Tetsu-to-Hagané. 79, 1101 (1993)
8) Yoshie, A. et al.: Shinnittetsu Giho. (370), 27 (1999)
9) Toda, M. et al.: J. Jpn. Soc. Technol. Plast. 29, 977 (1988)
10) Takai, K. et al.: Tetsu-to-Hagané. 81, 1025 (1995)
11) Kimura, Y. et al.: Transactions of the Japan Society of Mechanical Engineers. 84, 1 (2018)
12) Narumi, R. et al.: Netsu Shori. 61 (6), 309 (2021)
13) Funayama, T.: Shinnittetsu Sumikin Giho. (406), 43 (2016)
14) Leslie, W.C., translated and edited by Koda, S.: Leslie’s Materials Science of Steel. Maruzen, 1985, p.175
15) Irvine, K.J. et al.: J. Iron Steel Inst. 187, 292 (1957)
16) Osakada, K. et al.: CIRP. 30 (1), 135 (1981)
17) Cold Forging Subcommittee Materials Research Group: J. Jpn. Soc. Technol. Plast. 22 (241), 139 (1981)

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