

High-Strength Cold-Rolled Steel Sheet for Automotive Structural Components Utilizing Water Quenching Continuous Annealing Process (WQ-CAL)

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Abstract:

JFE Steel has developed and commercialized high-strength cold-rolled steel sheets with a tensile strength range of 780 to 1 470 MPa, applicable to automotive structural components, by utilizing its unique water quenching continuous annealing process (WQ-CAL). For the application of ultrahigh-strength steel sheet with a tensile strength of 1 320 MPa or higher, it is essential to ensure cold press formability and spot weldability, and to consider delayed fracture. These challenges associated with ultrahigh-strength steel have been addressed through low-alloy component design and microstructure control, leveraging the world's fastest rapid cooling capabilities of WQ-CAL, resulting in the commercialization of ultrahigh-strength steel sheet suitable for automotive structural components. Martensitic steel sheet with a strength range of 1 320 to 1 700 MPa demonstrates superior productivity, cost-effectiveness, and low environmental impacts compared with hot-pressed steel sheet, and is expected to see further expansion in applications as ultrahigh-strength steel sheets, contributing to vehicle lightweighting.

1. Introduction

The functions required in automobiles have diversified in recent years, and the technological innovation called CASE, a general term for Connected, Autonomous, Shared & Service and Electric, is progressing. In particular, electrification contributes to reduction of CO₂ emissions, but because electric vehicles (EVs) have a shorter cruising range than conventional gasoline-powered automobiles, further vehicle lightweighting is a common challenge for EVs and gasoline-powered automobiles. In response to the sweeping

transformation of automobiles represented by CASE, steel makers are required to develop innovative new steel materials.

Figure 1 shows the history of the development of cold-rolled steel sheets at JFE Steel. In the 1970s, JFE was the world's first steel maker to begin production of cold-rolled steel sheets by the continuous annealing process, and developed steel sheet products with a combination of safety and practicality by achieving improvements in the formability, delayed fracture characteristics and spot weldability necessary to expand the applications of high-strength steel sheets by low-alloy component design and control of the metal microstructure utilizing the full capabilities of the continuous annealing line with water quenching equipment (WQ-CAL) shown in Photo 1¹⁾.

This paper presents an overview of JFE Steel's proprietary WQ-CAL technology, and the features, concept of material design and examples of applications of 1 320 to 1 700 MPa grade martensitic steel sheets manufactured using the WQ-CAL.

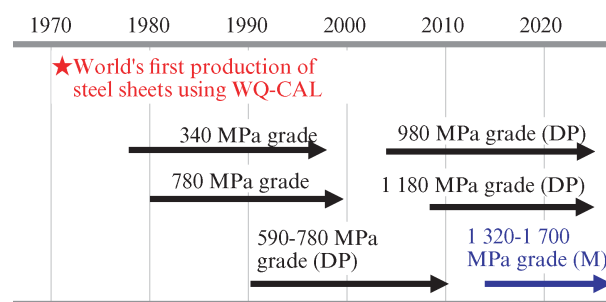


Fig. 1 Development process utilizing WQ-CAL equipment
DP: Dual phase, M: Martensite

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Photo 1 Fukuyama No.3 continuous annealing line equipped with water quenching (WQ-CAL) ¹⁾

2. WQ-CAL Manufacturing Technology and Material Development Utilizing the WQ-CAL

Utilizing the WQ-CAL, which was developed independently by JFE Steel and possesses the world's fastest cooling capacity, exceeding 1 000 °C/s, JFE Steel succeeded in developing a line of high-strength cold-rolled steel sheet products with strength from 780 MPa to 1 470 MPa grade¹⁻⁴⁾. An outline of the equipment configuration of the WQ-CAL and the heat cycle applied

to steel sheets are shown schematically in Fig. 2. By appropriately controlling the annealing conditions, the WQ-CAL can produce both DP (Dual Phase) steel sheets and martensitic single-phase steel sheets as required.

In production of DP steel sheets using the WQ-CAL, control of the volume fraction of the hard second phase by the annealing temperature and water quenching temperature, and control of the hardness of the hard second phase by the tempering temperature are performed separately. As a representative example of this, Fig. 3 shows the balance of the elongation and the hole-expanding ratio of 980 MPa grade DP steel sheets. A trade-off relationship exists between these two properties, as the hole expanding ratio tends to decrease when elongation is increased. However, the 980 MPa grade steel sheets manufactured by the WQ-CAL achieved an excellent hole-expanding ratio while maintaining satisfactory elongation. This was possible because good ductility is maintained by controlling the ferrite fraction by optimizing the annealing temperature and water quenching temperature of the WQ-CAL, while an excellent hole-expanding property was achieved by reducing the hardness difference between the ferrite and tempered martensite phases by optimizing the tempering temperature^{5,6)}.

Since the high cooling capacity of the WQ-CAL enables high strengthening while reducing the addition of C and hardening elements, it is extremely suitable for manufacturing martensitic steel sheets with out-

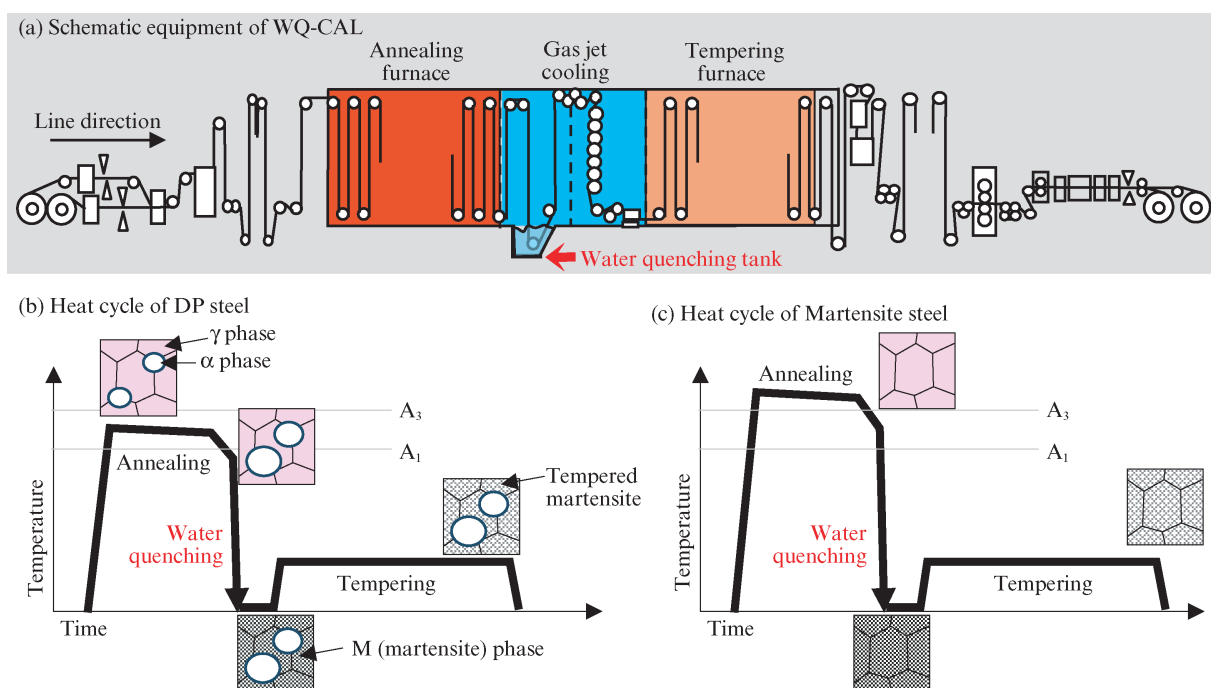


Fig. 2 (a) Equipment configuration of a continuous annealing line, and heat treatment patterns and microstructural changes of (b) DP (Dual phase) steel sheets and (c) martensitic steel sheets
 γ phase: Austenite phase, α phase: Ferrite phase

Table 1 Line up of 1 320–1 470 MPa grade martensitic steel

TS grade	Name	Mechanical properties					C _{eq}
		YS (MPa)	TS (MPa)	El (%)	λ (%)	R/t	
1 320	1320CR	1 160	1 330	7	50	2.5	0.24
1 470	1470CR	1 270	1 510	7	50	3.2	0.27
1 700	1700CR	1 450	1 750	7	40	3.6	0.38

YS: Yield strength TS: Tensile strength El: Elongation

λ : Hole expanding ratio

R/t: Radius to thickness ratio. It indicates the limit at which cracking does not occur

C_{eq}: Carbon equivalent ($= C + Si/30 + Mn/20$)

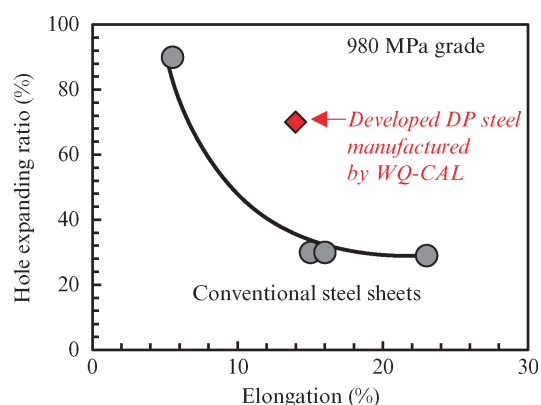


Fig. 3 Elongation-Hole expanding ratio balance of 980 MPa grade DP steel sheets

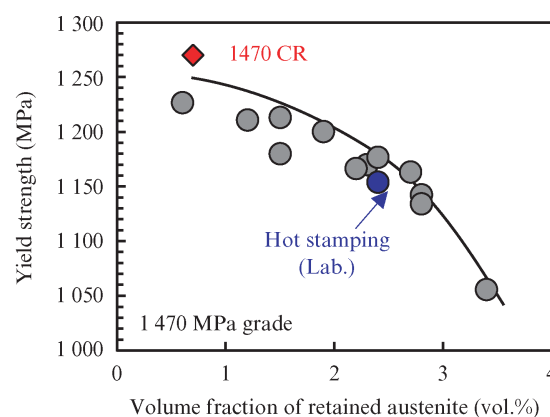


Fig. 4 Relationship between the amount of retained austenite and yield strength in 1 470 MPa grade steel sheets

standing delayed fracture characteristics and spot weldability. Moreover, an excellent hole expanding property and cold press formability, including bendability, etc., can also be achieved by applying rapid cooling to reduce microstructural heterogeneity to the absolute minimum. Although the hot stamping is known as a method for manufacturing components in which strength of 1 470 MPa or higher is required, this process requires heating of steel sheets to a high temperature, removal of oxidation scale from the formed sheets, and post-treatment processes such as laser trimming, etc. after press forming. As a result, the equipment cost is high, and large consumption of thermal energy in the heating process also has a significant environmental impact. The cold press method is an excellent process that addresses these issues, as it has the advantages of excellent productivity, cost-effectiveness and lower environmental impacts, and JFE's 1 470 MPa grade martensitic steel sheet, which is used in the cold press process, has received a high evaluation from customers as an alternative to hot press formed components.

3. Development Status of Recent Martensitic Steel Sheets Manufactured by the WQ-CAL

Table 1 shows JFE Steel's martensitic steel sheets

and their representative properties. JFE's 1 320, 1 470 and 1 700 MPa grade martensitic steel sheets (hereinafter, 1320CR, 1470CR and 1700CR) have the world's highest level of strength as steel sheets for cold forming. As described in the previous chapter, in these steel sheets, high strength is effectively achieved while reducing the addition of C and hardening elements. As products with both high impact performance and good delayed fracture characteristics and spot weldability, these steel sheets are used as materials for impact-resistant components of automobiles. In addition, since heterogeneity of the microstructure of the steel sheets is reduced to the absolute minimum by rapid cooling, they also possess an excellent cold press formability, such as hole-expanding ratio (λ) and bendability (R/t). This chapter introduces the features of martensitic steel sheets making maximum use of the advantages of the WQ-CAL.

3.1 Impact Resistance Characteristics

The first feature of martensitic steel sheets is excellent impact resistance due to their high yield strength. The high yield strength of martensitic steel sheets is achieved by a component design in which retained austenite, which is a cause of reduced yield strength, is minimized as far as possible. Figure 4 shows the relationship between the amount of retained austenite and

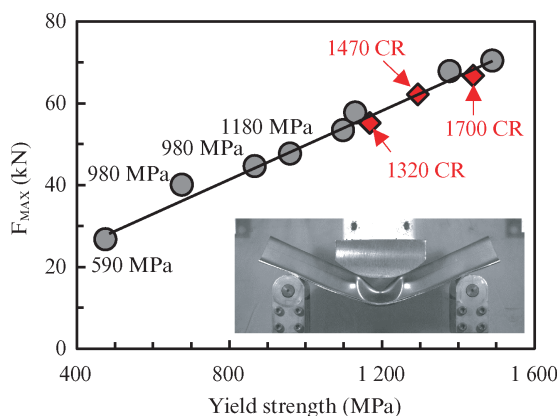


Fig. 5 Relationship between impact resistance and yield strength⁸⁾

yield strength in the 1 470 MPa grade steel sheet. The figure also shows the results for a 1.5 GPa grade hot stamping material produced in the laboratory. Although yield strength shows a tendency to decrease as the volume of retained austenite increases, because carbon partitioning between the martensite and austenite phases during cooling is controlled⁷⁾, almost no retained austenite forms in the 1470CR, and as a result, this material possesses higher yield strength than the 1.5 GPa hot stamping material.

Figure 5 shows the relationship of impact resistance and yield strength in the three-point bending test of M-shaped hat components (length: 400 mm) simulating automotive components produced using steel sheets with strength levels from 590 MPa to 1 700 MPa grade with a steel punch having a radius of R100 in the center of the component⁸⁾. The yield strength of 1470CR is 1 270 MPa, while 1700CR has a higher yield strength of 1 430 MPa. Therefore, 1470CR was compared with 1.5 GPa grade hot stamping materials with yield strengths of 1 000 to 1 200 MPa⁹⁾ and 1.8 GPa grade hot stamping materials with yield strengths of 1 100 to 1 400 MPa. The results showed that the 1470CR has yield strength superior to that of the hot stamping materials of the same strength.

3.2 Delayed Fracture Characteristics

In ultra-high strength steel sheets of 1 180 MPa grade and higher, delayed fracture during use as automotive components is a concern¹⁰⁾. Delayed fracture is an embrittlement and fracture phenomenon of steel caused by hydrogen absorbed into the steel; its controlling factors are considered to be material factors such as strength, microstructure, etc., applied stress and the amount of absorbed hydrogen. Therefore, when applying ultra-high strength steel to automotive components, it is also necessary to consider measures to prevent delayed fracture.

It is known that reducing the addition of Mn, which

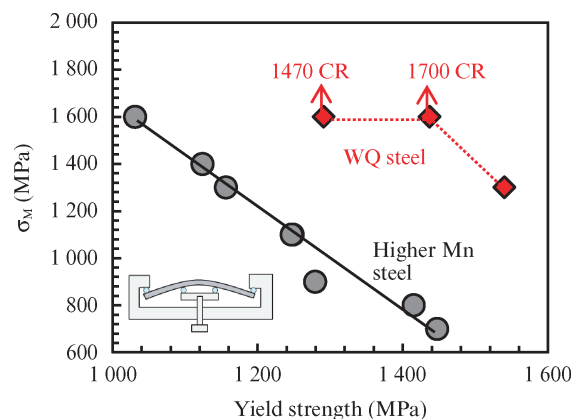


Fig. 6 Relationship between maximum unfractured stress and yield strength σ_M : Maximum unfractured stress

is a hardening element, is effective for suppressing delayed fracture of ultra-high strength steel. The existence of Mn plays a critical role as a material factor in delayed fracture. Concretely, MnS is considered to be the cause of the reduced delayed fracture resistance, as it becomes a point of origin for stress concentrations and hydrogen absorption¹¹⁾. JFE Steel's 1320CR, 1470CR and 1700CR are designed to minimize the addition of the hardening element Mn by utilizing the high cooling capacity of the WQ-CAL, and thereby improve resistance against delayed fracture. **Figure 6** shows the maximum unfractured stress after 96 hours when 4-point bending stress was applied to test pieces prepared using steel sheets with different strength levels, and hydrogen absorption was performed by immersing the test pieces in 0.1N-HCl. In the higher Mn steel, which was prepared in the laboratory, the maximum unfractured strength showed a tendency to decrease as yield strength increased, but cracking was not observed in JFE Steel's 1470CR and 1700CR, even under a maximum stress of 1 600 MPa. Since this delayed fracture evaluation confirmed that 1470CR and 1700CR have sufficient performance, a model component of an automotive door impact beam was prepared using 1700CR, and was immersed for 96 hours in a pH1 hydrochloric acid solution, considering the effect of press forming on delayed fracture. The results are shown in **Photo 2**. Cracking was not observed in the component after immersion, confirming that JFE Steel's 1700CR also possesses excellent delayed fracture resistance in actual component shapes.

Thus, these results confirmed that 1470CR and 1700CR, in which microstructural heterogeneities in the steel sheets are reduced to the absolute limit by rapid cooling and the component design minimizes addition of Mn, also have excellent hydrogen embrittlement characteristics due to uniform hardness in microns.

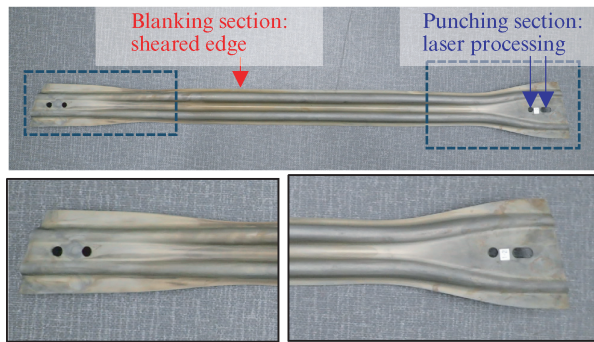


Photo 2 Delayed fracture evaluation results of 1700CR model components (after 96 hours of immersion in pH1 hydrochloric acid)

3.3 Spot Weldability

Since the hardness of martensite depends on the C content, the amount of added C inevitably increases in steel sheets with higher strength. However, 1320CR, 1470CR and 1700CR are designed to minimize the carbon equivalent, which affects spot weldability, by utilizing the high cooling capacity of the WQ-CAL. **Figure 7** shows the results of an evaluation of the maximum load to fracture (i.e., joint strength of the weld) in a tensile test at 10 mm/min of cruciform tensile test pieces with a nugget diameter of $5\sqrt{t}$, which were prepared by spot welding steel sheets of the same steel grade and different strength levels. Although the strength of the welded joints shows a tendency to decrease as yield strength increases, it can be understood that 1470CR and 1700CR can be strengthened effectively, while suppressing the addition of C and hardening elements, due to the high cooling capacity of the WQ-CAL, and the developed steels have higher joint strength than the hot stamping material with the same yield strength level.

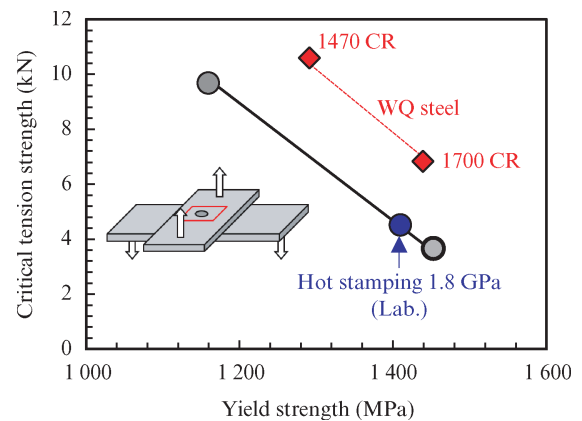


Fig. 7 Relationship between critical tension strength of welded points and yield strength

4. Examples of Applications of Martensitic Steel Sheets

Practical application of the 1 320 MPa and 1 470 MPa grade martensitic steel sheets manufactured by the WQ-CAL, as described in the previous chapter, is progressing, centering on automotive structural components in which impact resistance is required. **Figure 8** shows the components in which these steels were adopted to date, and **Photo 3** shows a roof center reinforcement as an example of the application of 1470CR¹²⁾. In comparison with the conventional structure, automotive lightweighting of approximately 13% can be achieved by applying ultra-high strength steel in these components.

Photo 4 shows the result of press-forming of 1700CR, which was developed to achieve a larger lightweighting effect, with an actual die simulating a bumper reinforcement. The results confirmed that bumpers of the 1 700 MPa grade, which is the world's highest level, can be manufactured by cold press forming. Since further lightweighting can be expected, it is assumed that these materials will replace the conven-

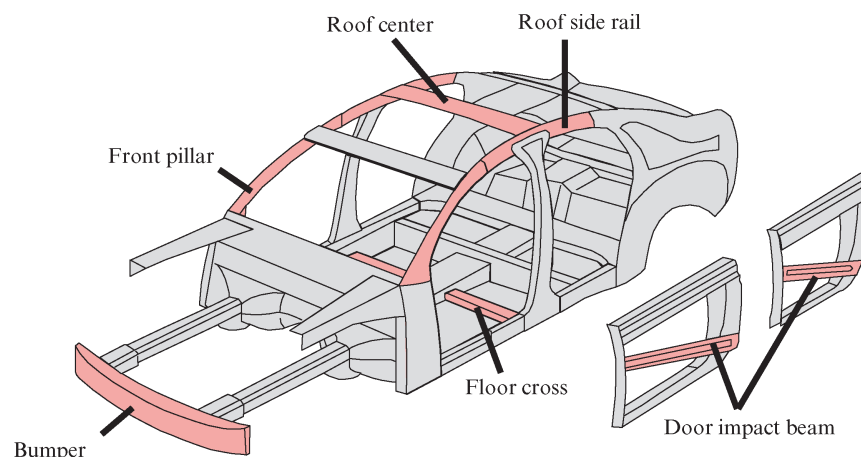


Fig. 8 Automotive structural parts that utilize martensitic cold-rolled steel sheet

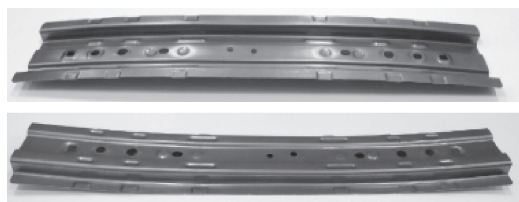


Photo 3 Roof center reinforcement component made of 1 470 MPa grade martensitic steel sheet¹²⁾



Photo 4 Bumper reinforcement parts component made of 1 700 MPa grade martensitic steel sheet

tional 1.8 GPa and 2.0 GPa hot stamping materials, and in fact, evaluations with the aim of application to actual vehicles are actually being carried out by many auto makers.

5. Conclusion

JFE Steel has commercialized 780 MPa to 1 470 MPa grade cold-rolled high-strength steel sheets by making the fullest use of the advantages of the water quenching continuous annealing process (WQ-CAL), which enables rapid cooling. JFE manufactures and sells these products as materials for automotive structural components. This paper introduced the features of martensitic steel sheets, focusing on the 1 470 MPa grade, together with examples of application, and also introduced the 1 700 MPa grade ultra-high strength steel, which was developed in response to needs for higher strength.

Since these martensitic steel sheets possess higher impact resistance, delayed fracture resistance and spot weldability than hot stamping materials of the same strength level, application as an alternative to hot stamping components is expected.

While deepening its partnerships with customers, JFE Steel will continue to propose total solutions that also include use technologies, and will promote the development of new products with the aim of supplying people- and environment-friendly steel sheets that contribute to the development of advanced vehicle bodies.

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