

Ultra-High Strength Hot-Rolled Steel Sheets for Automotive Chassis and Truck Frame Applications and its Utilization Technologies

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Abstract:

JFE Steel has developed hot-rolled ultra-high strength steel with tensile strengths of 980 and 1180 MPa, offering superior toughness, punchability, and bendability. This development contributes to the lightweighting of automobiles. These high-tensile materials are ideal for chassis components, and thinner parts are expected to improve driving performance and fuel efficiency. Utilization technologies are also being developed, including low-CO₂ gas-shielded arc welding and J-SKY MIGTM welding, which improve the fatigue strength and corrosion resistance of welded joints compared to conventional methods. Furthermore, JFE Steel has developed a micro-needle peening technique that enhances the fatigue strength of welded joints to a level comparable to the base material. These technologies achieve both durability and lightweighting for automotive components, promising significant advancements in the automotive industry. This paper discusses the details and practical applications of these innovations.

1. Introduction

In the automotive industry, lightweighting and high strength are demanded in vehicle bodies. In particular, lightweighting has become an important issue due to the increasing vehicle weight accompanying the progress of electrification in recent years. The use of high-strength steel sheets (hereinafter, high-strength steel) makes it possible to reduce the thickness of automotive components, resulting in improved driving performance and fuel economy, which in turn reduces CO₂ emissions. Moreover, the use of high-strength steel increases the strength of components of the same weight. In the truck sector, the advantages of high-strength steel are

also increasing due to strengthening of collision safety regulations. In addition, lightweighting of the truck frame by using high-strength steel makes it possible to increase the maximum payload, thereby reducing transportation costs.

At present, hot-rolled steel sheets with tensile strengths of 440 MPa to 590 MPa are mainly used in chassis components, at the same time, needs for ultra-high-strength steels with strength levels exceeding the 980 MPa grade are increasing. Even among automotive components, chassis components such as suspension arms, frames, etc. are critical parts that support the basic function of vehicles. Therefore, reliability against brittle fracture under impact loading and fatigue failure due to cyclic loading are required, but as the strength of steel sheets increases, toughness decreases. In addition, edge chipping may occur at the sheared edge in the punching and shearing processes frequently used in automotive components if the processing conditions are not appropriate. Since edge chipping can easily result in decreased fatigue strength in steel sheets as strength increases, steel sheets with good resistance to edge chipping of the shear edges are demanded.

Gas-shielded arc welding is used in the production of chassis components. However, in welds, there is little increase in the fatigue strength of welded joints, even if high-strength steel is used, due to the large stress concentration and existence of tensile residual stress at the weld toe¹⁾. Since this tendency is particularly large in lap fillet welded joints of thin steel sheets, where geometric stress concentrations are large^{2,3)}, securing the fatigue strength of welded joints is a challenge for expanding the application of high-strength steel to chassis components. Furthermore, since chassis components are exposed to an environment where rust eas-

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ily occurs due to water splash from the road surface during travel, corrosion resistance (corrosion protection) is also important in terms of durability. Although chassis components are painted to secure corrosion resistance, paintability is reduced by oxides (weld slag) adhering to the weld bead surface, etc., and as a result, reduced corrosion resistance of joints is a problem.

Against this background, JFE Steel is developing 980 MPa to 1 180 MPa grade hot-rolled ultra-high-strength steels with excellent toughness, punchability and bendability by utilizing its proprietary steel sheet microstructure control technology. As use technologies for those steel sheets, the company has also developed arc welding technologies to reduce weld slag and a peening technology for the weld bead toe to improve the fatigue strength of welded joints. This paper introduces the details of these technologies and their practical application.

2. Development of Hot-Rolled Ultra-High-Strength Steel for Chassis Components

2.1 Material Design Concept

Since chassis components include many burring parts and stretch-flange forming parts, it is necessary to select a steel sheet microstructure that displays an excellent hole expansion ability. In dual-phase steel, Hasegawa et al.⁴⁾ showed that void initiation and growth at the ferrite-martensite interface is accelerated as the hardness difference between the two phases increases, reducing the hole expansion ability. Since this suggests that reducing the hardness difference between the phases is effective for improving the hole expansion ability, steels with a microstructure having a homogeneous microhardness distribution were targeted. A homogeneous microhardness distribution is also advantageous for improving bendability.

Next, single-phase steels with different strengthening mechanisms were prepared, and their impact resistance was evaluated. Steels with a bainitic microstruc-

ture achieved mainly by dislocation strengthening, and with a ferritic microstructure achieved mainly by precipitation strengthening, were produced by adjusting the alloy components and coiling temperature to obtain tensile strength of the 980 MPa grade. These steels are both low-carbon steels with carbon content of 0.1 mass% or less. Charpy impact tests of these two steel types were carried out, and their ductile-brittle transition temperatures (DBTT) were compared. The size of the test pieces was 10 mm×55 mm×2.9 mm t, and a V-notch with a depth of 2 mm was introduced by machining so that the rolling direction became the direction of crack propagation.

Figure 1 shows the Charpy transition curves. From the fracture surface transition curves, it was found that the DBTT of the ferritic steel was -20°C , while the DBTT of the bainitic steel was -60°C , indicating that the bainitic steel possesses superior impact resistance.

Following this, the condition of shear edge in punching was investigated. Punched holes were punched with a punch having a diameter of 10 mm and a clearance (sheet-thickness ratio of the punch and die) set to 10% or 20%. **Figure 2** shows the appearance of the punching shear edge. While a smooth punching shear edge was formed with the bainitic steel, the ferritic steel displayed cracking and edge chipping⁵⁾ due to brittle fracture of the punching shear edge when the punching clearance was 20%. The fact that a smooth, crack-free punching shear edge could be obtained with the bainitic steel is attributed to its superior toughness.

2.2 Hot-Rolled High-Strength Steel Production Technology and Examples of Application

Based on the results described above, material development was carried out focusing mainly on the bainitic microstructure. As shown in **Fig. 3**, when producing steel with a bainitic microstructure, cooling to $400\text{--}500^{\circ}\text{C}$ on the run-out table is necessary. In this temperature region, called the transition boiling region, the cooling stop temperature tends to become unstable⁶⁾, and the material control becomes difficult. There-

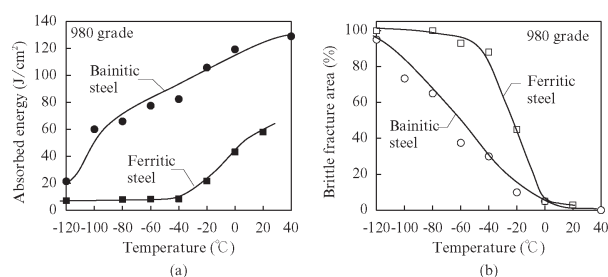


Fig. 1 Charpy impact test result in bainitic steel and ferritic steel (980 MPa-grade)

(a) Energy transition curves and (b) ductile-brittle transition curves

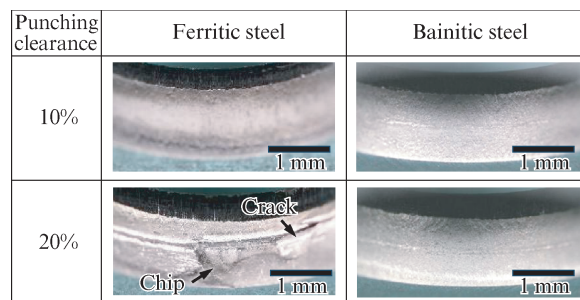


Fig. 2 Appearance of punching shear edge (thickness: 2.9 mm)

Table 1 Representative mechanical properties and applications of hot-rolled ultra-high strength steel

Steel	t (mm)	YS (MPa)	TS (MPa)	El (%)	λ (%)	R/t	Car chassis (arms, members)	Truck chassis (cross members, underrun protectors)
JFE-HA780SB	2.9	710	810	17	70	0.5	Mass production	Mass production
JFE-HA980R	3.2	900	1 010	12	50	1.4	Mass production	Mass production
JFE-HA980SB	2.9	860	1 010	12	60	1.4	Mass production	Mass production
1180	2.9	1 040	1 220	9	35	2.4	-	Development

t: thickness, YS: yield strength, TS: tensile strength, El: elongation, λ : hole expansion ratio, R/t: 90°-V-bendability (R: minimum bend radius)

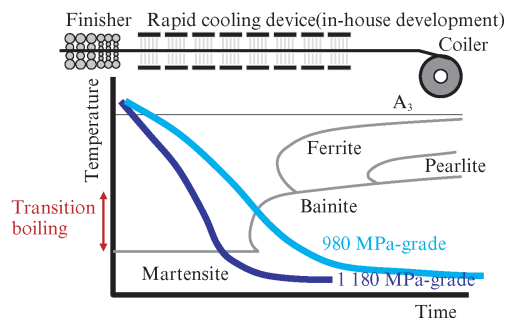


Fig. 3 Cooling process on run-out table for hot-rolled 980-1180 MPa ultra-high strength steel (schematic image)

fore, JFE Steel carried out in-house development of a cooling technology that can maintain a nucleate boiling condition across the entire temperature region, and utilized this technology to develop a 980 MPa grade bainitic steel. Since this technology can also achieve rapid cooling, quenching to the martensite transformation temperature is possible. This made it possible to increase tensile strength from 980 MPa grade to 1180 MPa grade with almost no increase in alloying elements. **Table 1** shows the representative mechanical properties of the developed steel and the application to actual vehicle components.

3. Development of Arc Welding Technologies for Chassis

3.1 Issues for Welding of Chassis Components Using High-Strength Steel

Since it is essential to secure durability and stiffness in chassis components, as mentioned above, corrosion resistance and fatigue strength are required properties of the welded joints. JFE Steel developed welding technologies that improve these joint properties without using special welding equipment or welding consumables⁷⁾. The following introduces a low-CO₂ gas-shielded arc welding and J-SKY MIGTM welding.

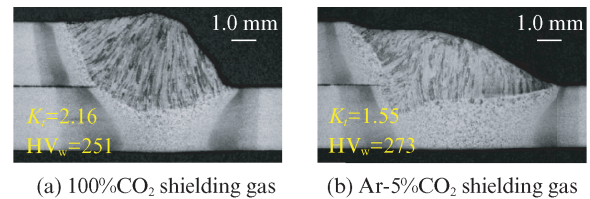


Fig. 4 Cross-sectional macrostructures of weld¹¹⁾

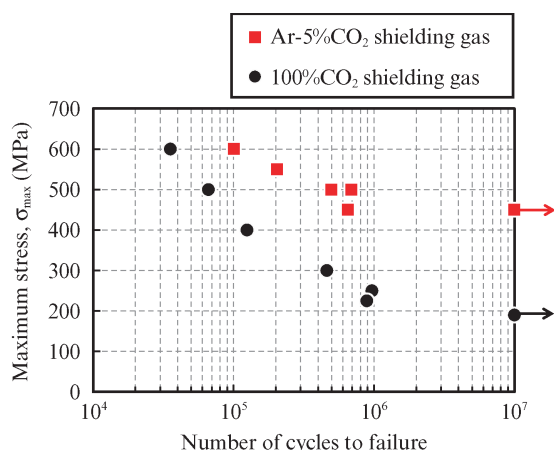
3.2 Fatigue Strength Improvement Effect of Low-CO₂ Gas-Shielded Arc Welding

The fatigue strength of welded joints is reduced by stress concentration at the weld bead toe. To address this problem, JFE Steel developed low-CO₂ gas-shielded arc welding, in which the mixing ratio of the active gas (CO₂) is reduced to 5%⁸⁻¹⁰⁾.

Figure 4 shows the cross-sectional macrostructures of welded joints when using (a) 100% CO₂ shielding gas and (b) Ar-5% CO₂ mixed gas, in which the CO₂ ratio is reduced to 5%¹¹⁾. Focusing on the weld toe profile, when using Ar-5% CO₂, the bead width and toe radius increase, and the stress concentration factor K_t decreases. It is known that the specific heat of the CO₂ gas is large and the thermal pinch effect promotes arc constriction^{12,13)}. Since arc constriction is weakened by the low CO₂ ratio of the Ar-5% CO₂ mixed gas, it is thought that a smooth toe profile can be obtained by the low-CO₂ welding technology.

Looking next at the hardness of the weld metal, the hardness HV_w of the weld metal tends to increase in Ar-5% CO₂ joints. This is attributed to suppression of oxide slag formation¹⁴⁾ by the Ar-5% CO₂ mixed gas, which has a low CO₂ ratio in the shielding gas, making it easy to maintain the alloying elements in the weld metal.

The results of a plane bending fatigue test of the respective welded joints are shown in **Fig. 5**¹¹⁾. The plots in the figure show the results of a fatigue test with pulsating loading of all specimens. In comparison with the 100% CO₂ joints, the Ar-5% CO₂ joints with a smoothed weld toe (i.e., reduced K_t value) showed substantial increases in both fatigue life and fatigue strength.

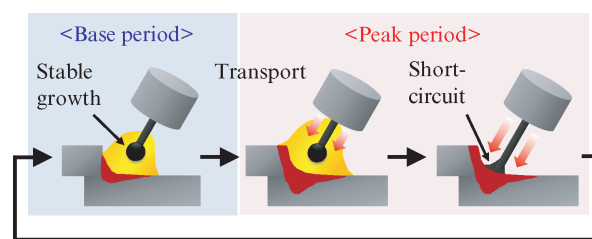
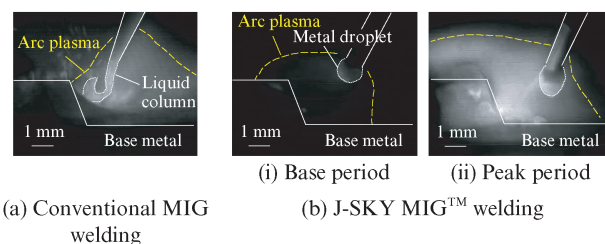
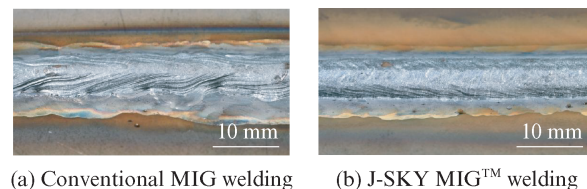
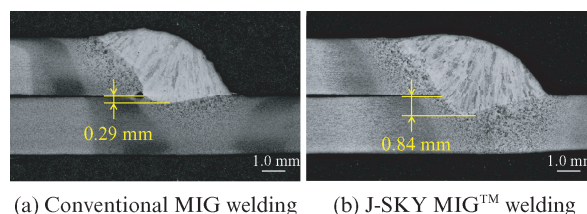
Fig. 5 Result of fatigue test of weld joint¹¹⁾

3.3 J-SKY MIG™ Welding Contributing to Minimization of Welding Slag Formation

The principal cause of reduced corrosion resistance of welded joints is the formation and adherence of weld slag, which is an oxide. Suppressing the oxidation reaction by reducing the CO₂ gas ratio is effective for reducing slag formation. The greatest effect of this approach can be seen in MIG (Metal Inert Gas) welding using pure Ar gas, which does not contain CO₂ gas, in the shielding gas. However, if the CO₂ ratio is lower than 5%, arc wander (arc blow) and instability of metal transfer will generally occur, resulting in meandering and waving of the weld bead. To eliminate these behaviors, JFE developed a new MIG welding technology, J-SKY MIG, utilizing high current pulse control^{15,16)}.

In conventional constant current MIG welding, metal transfer becomes unstable because the electromagnetic pinch force that detaches the molten metal droplet from the wire tip is inadequate. Focusing on this fact, in J-SKY MIG welding, as shown in Fig. 6, metal transfer was controlled to periodic short-circuit transfer¹⁶⁾. Figure 7 shows photographic images of the metal transfer behaviors in conventional MIG welding and J-SKY MIG welding¹⁵⁾. In conventional MIG welding, a liquid column is generated continuously, and irregular metal transfer occurs. In J-SKY MIG welding, the molten region is limited to the wire tip in the base period, enabling stable growth and a constant size of the molten metal droplet. Then, in the peak period, the droplet at the wire tip is transported to the weld pool by a high-speed plasma jet induced by a high current pulse, so that one short circuit occurs with each pulse current, thereby realizing periodic, stable short-circuit transfer.

Figure 8 shows the appearance of the weld beads¹⁵⁾. With J-SKY MIG welding, joints with a uniform weld bead are obtained, and because the formation of weld

Fig. 6 Concept of short-circuit transfer control¹⁶⁾Fig. 7 Photographs of metal transfer behaviors¹⁵⁾Fig. 8 Photographs of weld bead appearance¹⁵⁾Fig. 9 Cross-sectional macrostructures of weld¹⁶⁾

slag (oxide) is suppressed by using pure Ar gas, adherence of weld slag is extremely slight. This is considered to improve the corrosion resistance of welded joints.

Figure 9 shows the cross-sectional macrostructures of welds by (a) conventional MIG welding and (b) J-SKY MIG welding¹⁶⁾. As one problem in MIG welding using pure Ar gas, it is generally difficult to obtain a deep penetration depth because the heat input is easily dissipated by spreading of the arc. However, in contrast to the penetration depth of 0.29 mm obtained by conventional MIG welding, the penetration depth with J-SKY MIG welding is 0.84 mm, achieving an improvement of approximately 2.9 times. This is considered to be the result of an increase in the heat input to the base metal owing to the higher temperature of the arc generated by the high current pulse during the

peak period.

4. Fatigue Strength Improvement Technology for Arc Welds

4.1 Improvement of Weld Strength by the Micro-Needle Penning (MNP) Method

As a fatigue strength improvement technology for arc welds in automotive applications, Fujimoto et al.¹⁷⁾ proposed a method for improving the fatigue strength of arc-welded joints of 1.5 GPa grade steel sheets by a shot peening method. This method utilizes the plastic deformation of the material surface by projection of shot media, which improves fatigue strength by introducing compressive residual stress and a work-hardened layer. However, practical application has not progressed because countermeasures to prevent scattering of the shot media and countermeasures to prevent carryover to the next process are necessary. On the other hand, the needle peening method, in which the weld toe is struck with pins, is known in the bridge sector and other fields¹⁸⁾. In addition to compressive residual stress and work hardening, this method can also expand the toe radius (thereby reducing stress concentration) by imprinting a pin geometry with a large radius of curvature on the weld toe.

JFE Steel developed the improved Micro-Needle Penning (MNP) method, which is suitable for automotive production lines, by scaling-down needle peening¹⁹⁾. By using the MNP method, a fatigue strength improvement effect comparable to that of shot peening can be obtained by the compressive residual stress and work-hardening layer introduced in the peened area^{20,21)}.

Figure 10 shows the MNP tool and the condition of peening treatment. Here, an electric marking pen equipped with an impact pin with a tip diameter of 0.2 mm was used. With this method, the small contact area between the tool and the target weld allows robot handling, resulting in improved productivity in comparison with shot peening or conventional needle peening. Furthermore, since localized processing is also possible, part deformation can be held to the minimum.

Figure 11 shows the fatigue strength improvement effect of the MNP method in lapped fillet welded joints. The arc welding shielding gas is Ar-20%CO₂. Without MNP treatment, the fatigue strength of welded joints does not improve, even if the base material strength is increased. However, with MNP treatment, fatigue strength is significantly improved, and fatigue strength comparable to the base metal strength can be obtained.

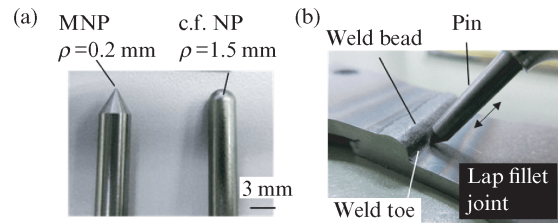


Fig. 10 Micro needle peening (MNP)¹⁹⁾

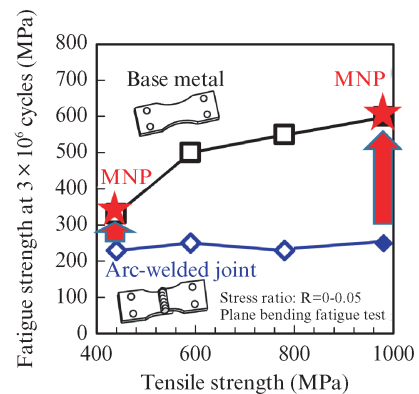


Fig. 11 Improvement in fatigue strength of arc-welded joint^{19, 22, 23)} (revised)

4.2 Development of Automated Processing System

JFE also studied automation of the MNP method for productivity improvement. Since the impact load of treatment by general pneumatic peening is several kN (with 4 kN as a representative value²⁰⁾), it is necessary to manufacture large-scale equipment with high stiffness. In contrast, since the impact load of MNP is about 200 N²⁰⁾, it is possible to mount the MNP equipment on a robot arm or other machine with comparatively low stiffness. **Figure 12** shows a prototype automated MNP treatment system. This system uses a three-stage processing steps comprising ① Shape measurement of the weld bead by a shape measurement device, ② Analysis of the coordinates of the weld toe and creation of a robot motion program and ③ MNP treatment. This system made it possible to place indentations accurately and with high repeatability. As the result of a verification of its robustness by treatment using diverse peening patterns, it was found that the fatigue strength improvement effect generally saturates if the residual slag on the weld toe is destroyed and the metallic luster is exposed¹⁹⁾.

4.3 Fatigue Improvement of Actual Components

MNP treatment of actual commercially-available components (lower arm) was performed using a prototype of the automated processing system, and the effect

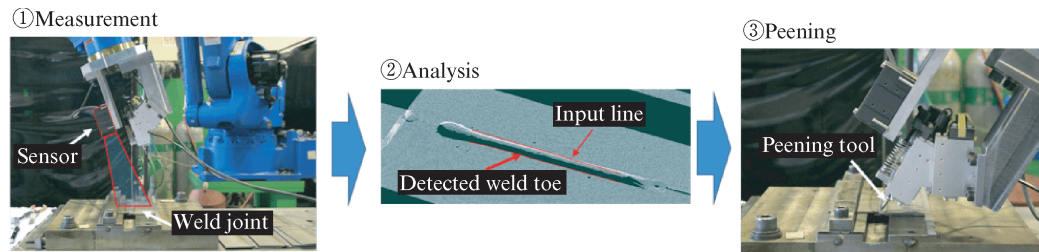


Fig. 12 Automated processing system incorporating shape measurement device and weld toe detection software¹⁹⁾

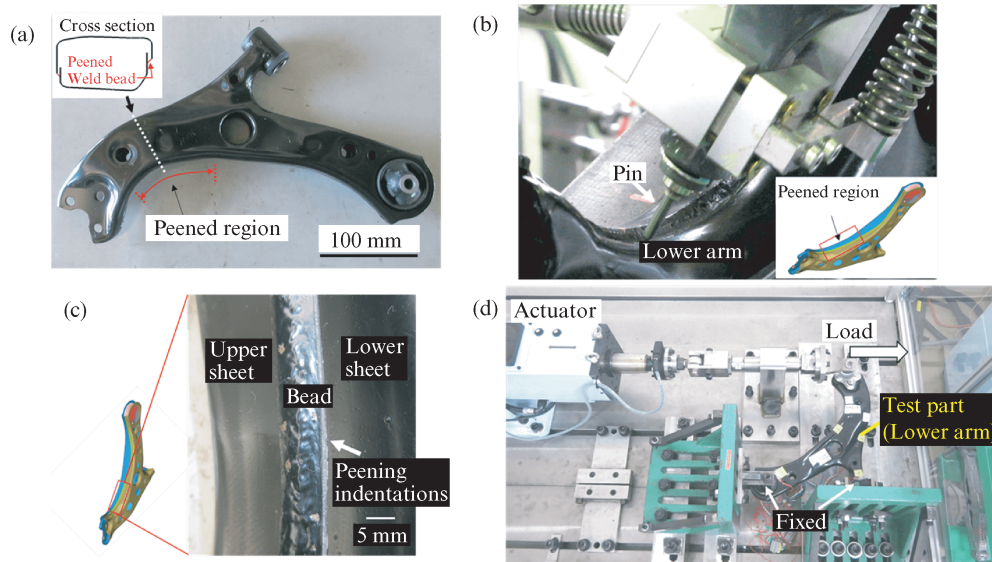


Fig. 13 Application test to actual part
(a) Lower arm (b) Appearance of peening operation (c) Weld bead after peening (d) Fatigue test¹⁹⁾

was verified by performing fatigue test. **Figure 13** shows a schematic diagram of the test. A fatigue test was carried out after applying MNP treatment to the toe of the curved weld bead. The stress range and stress ratio of the applied load were 10.5 kN and -0.5 , respectively, and the loading frequency was 1 Hz. As the results of the fatigue test, the as-received component fractured at 3×10^5 cycles, but no fatigue cracks were observed in the MNP-treated component, even after loading 1×10^6 cycles, confirming the fatigue life improvement effect of MNP treatment of automotive suspension components.

5. Conclusion

This paper described the development of hot-rolled ultra-high strength steel with the aim of achieving high-strength lightweighting in automotive chassis components, and welding technologies for the application of those chassis components and a fatigue strength improvement technology for welded joints. In particular, targeting 980 MPa grade and 1 180 MPa grade steel sheets, JFE Steel succeeded in developing steel sheets

with excellent properties by utilizing microstructure control technologies that consider toughness and formability. The introduction of a low- CO_2 gas-shielded arc welding technology and J-SKY MIGTM welding have improved the fatigue strength and corrosion resistance of welded joints, heightening the reliability of chassis components. JFE Steel also succeeded in developing a Micro-Needle Peening (MNP) technology which dramatically improves the fatigue strength of welded joints.

The application of these technologies to actual automotive components is under study, and in some cases, these technologies have already reached the stage of practical application. JFE Steel is committed to contributing to a sustainable automotive industry by continuing to deepen its collaboration with customers and providing innovative solutions.

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