

Steel Sheets for Automobiles and its Application Technologies

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Abstract:

JFE Steel has developed application technologies to maximize the performance of high-strength steel sheets in addition to high-strength steel sheets with high performance, including vehicle body structural design and press forming and welding methods for auto parts. By providing comprehensive solutions that include materials and application technologies, JFE Steel supports customers to reduce vehicle body weight and improve crash safety performance, and contributes to the realization of a future carbon-neutral society through reducing CO₂ emissions during vehicle operation. This paper introduces JFE Steel's characteristic cold-rolled and galvanized high-strength steel sheets and hot-rolled high strength steel sheets, and outlines the application technology.

1. Introduction

To realize a carbon-neutral society by 2050, reduction of CO₂ emissions in material manufacturing processes is not only essential, but also lightweighting of automobile bodies, in which large amounts of steel products are used, is also an important challenge¹⁾. Since designing and building strong, tough automobile bodies using thinner materials by applying high-strength steel sheets to automobile frame components is effective for simultaneously satisfying auto body lightweighting and improvement of crash safety performance, application of high-strength steel sheets to frame components has been increasing²⁾. Lightweighting of chassis components is also an equally important issue, and adoption of high-strength steel sheets in those parts is continuing. As shown in Fig. 1, the strength of the steel sheets applied in these applications

is increasing year by year. Steel sheets with 1 470 MPa grade tensile strength are now used in frame components, and 980 MPa grade steel sheets are used in chassis parts. In recent years, production and sales of new energy vehicles beginning with electric vehicles has expanded. However, in electric vehicles in which a large battery is installed in the lower body, use of high strength materials in the frame components around the cabin is also essential for protecting the battery. From this viewpoint as well, expanded application of high-strength steel sheets is expected in the future³⁾.

The automobile body can be broadly divided into the cabin that protects the passengers, and frame components in the front and rear of the vehicle, which absorb energy in a collision. In the frame components surrounding the cabin, it is necessary to use ultra-high strength steel sheets that will not deform in a collision, and in the front and rear frame components, which are

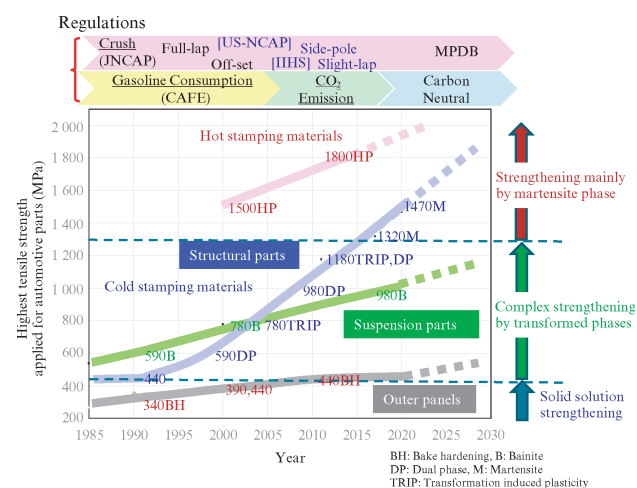


Fig. 1 Transition of application of HITEN to auto parts

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designed to absorb collision energy by deforming, application of high-strength steel sheets that can suppress fracture during deformation in a collision is required. JFE Steel has developed cold-rolled ultra-high strength steel sheets of 1 180 to 1 470 MPa grade as materials for the cabin, and 980 to 1 180 MPa grade galvanized high-strength steel sheets as materials for energy-absorption components. Moreover, since reduction of component manufacturing costs by integrating multiple parts to reduce the number of components has been demanded in recent years, JFE Steel is also developing integration technologies for components in which ultra-high strength steel sheets are applied⁴⁾. By combining these high-performance high-strength steel sheets and component integration technologies, JFE proposes automobile body structures consisting of a lightweight cabin that can withstand deformation in a collision and a front and rear frame with excellent energy-absorption performance to auto makers as a future auto body concept.

On the other hand, since it is known that press formability and weldability decrease as the strength of the materials increases, forming methods and welding methods that enable effective use of high-strength steel sheets are required. In addition, techniques for designing lightweight high-rigidity body structures using high-strength steel sheets are also essential. To respond to these needs, JFE Steel systematized its high-formability high-strength steel sheets as “JEFORMA™” (JFE Excellent FORMability)⁵⁾ and its application technologies for steel sheets as “JESOLVA™” (JFE Excellent SOLution for Vehicle Application) (Fig. 2)⁶⁾. To contribute to vehicle product development and improvement of product performance, JFE Steel has also carried out EVI (Early Vendor Involvement) activities, cooperating with auto makers from the initial stage of vehicle body development, and proposes comprehensive solutions that treat high-performance materials and their application technologies as a set.

In comparison with other materials, steel has the advantages of easy mass production, low cost and good recyclability, and from the viewpoint of environmental protection, JFE Steel supplies high-performance automotive high-strength steel sheets with an orientation toward cold stamping, which is advantageous for reducing CO₂ emissions in the part manufacturing process because the steel sheets are stamped at room temperature without heating.

The paper presents the JFE Steel’s line-up of cold-rolled high-strength steel sheets, galvanized high-strength steel sheets and hot-rolled high-strength steel sheets, together with an overview of application technologies for forming, welding, auto body design, etc. to achieve the performance of high-strength steel sheets

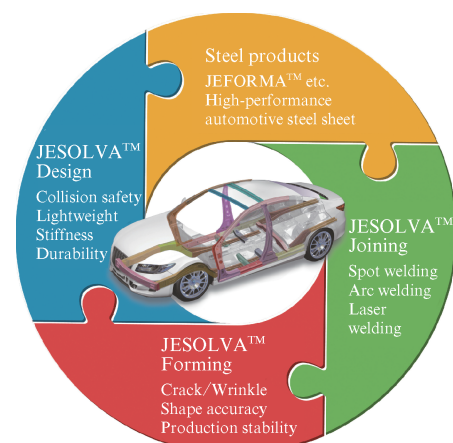


Fig. 2 Application technologies for applying steel sheets to auto parts: JESOLVA™

to the fullest possible extent.

2. JFE Steel’s Automotive High-Strength Steel Sheets and their Production Technologies

As the strength of steel increases, its press formability and weldability deteriorate, and at strengths of 1 180 MPa and higher, the phenomenon of delayed fracture, in which hydrogen atoms penetrated into the steel cause cracking, becomes a problem⁷⁾. To expand the application of high-strength steel sheets, high-strength steels that secure the formability and weldability required in the product and have good resistance against delayed fracture are necessary. Although high strength is achieved in sheets by adding several % of alloying elements, this causes changes in the state of the steel sheet surface during heat treatment, in some cases leading to deterioration of phosphatability or corrosion resistance after painting, or increased susceptibility to defects during hot-dip coating treatment for rust protection^{8,9)}. Practical application of high-strength steel sheets is only possible after solving all these issues. JFE Steel has achieved the production of high-performance high-strength steel sheets by high-level control of the formability of the base material and properties such as delayed fracture by utilizing various steel microstructure control technologies, and modification of the steel sheet surface to a condition suitable for phosphating or coating adhesion. This chapter presents an overview of the automotive high-strength steel sheets produced and developed by JFE Steel.

2.1 Cold-Rolled and Rust Resistant High-Strength Steel Sheets

JFE Steel mass-produces cold-rolled high-strength steel sheets up to 1 470 MPa grade and galvanized high-strength steel sheets (GA) up to 1 180 MPa grade. As next-generation high-strength steel sheets, JFE is

also working to commercialize 1 700 MPa grade cold-rolled steel sheets and GA of 1 470 MPa grade and higher.

The key points in manufacturing cold-rolled high-strength steel sheets are microstructure control to obtain the necessary material quality, including formability, weldability, resistance to delayed fracture, etc., and surface condition control of the steel sheets to secure the phosphatability required for good paintability. In material control, that is, microstructure control of cold-rolled steel sheets, there are few restrictions on the thermal history, as it is not necessary to apply a hot-dip Zn coating, and product design using a process that prioritizes material control is possible. JFE Steel has adopted a design that achieves high strength with a low carbon equivalent by using the WQ-CAL (Water Quenching Continuous Annealing Line). The WQ-CAL process, which was developed by JFE Steel, performs high-speed cooling by water quenching after annealing, is mainly used with high-strength steel sheets of 980 MPa grade and higher. These products have excellent weldability and extremely high delayed resistance. Annealing temperature control also makes it possible to control the volume fraction of ferrite as softer phase with high accuracy, enabling production of products with different formability balances, even in the same strength grade¹⁰⁾. The GJ-CAL (Gas Jet Continuous Annealing Line), which performs gas cooling after annealing, can produce high-formability steel sheets using the retained austenite phase, which is particularly effective for improving elongation characteristics. On the other hand, for surface condition control, production conditions have been optimized by clarifying the oxidation state of the alloying elements added to the steel in the annealing furnace, achieving a steel sheet surface condition that will good for phosphating treatment. Utilizing these technologies, JFE Steel achieved 1 310 MPa grade steel sheets in 2019 and 1 470 MPa grade steel sheets in 2020 as materials for automotive frame components.

When producing GA high-strength steel sheets, it is necessary to apply a hot-dip Zn coating to the steel sheet. This requires a coating process in which the steel strip is cooled to approximately 450–500°C after annealing and then immersed in a molten Zn coating bath, followed by a heating process to alloy the Fe of the steel strip and the Zn coating by heating to approximately 500–600°C. Since it is difficult to apply a water-quenching process, more alloying elements are added than in cold-rolled high-strength steel sheets to achieve the required strength. In spite of those restrictions, JFE Steel has achieved the necessary properties, without sacrificing high strength, by improvements in the composition design and thermal history. As an

Table 1 Lineup of JEFORMA™

Product type	Strength grade	Conventional	JEFORMA		
			Type1 (High El)	Type2 (HighEl-high λ)	Type3 (Super high El)
CR	590	●	●	△	●
	780	●	●	○	●
	980	●	●	○	●
	1180	●	●	○	●
GA	590	●	●	○	●
	780	●	●	○	●
	980	●	●	●	△
	1180	●	○	△	△

●: Commercial production ○: Developed △: Under development

additional challenge, in high-strength steel sheets, alloying elements such as Mn, Si, etc. may form oxides that hinder coating treatment on the steel sheet surface during annealing. To solve this problem, JFE precisely controls the oxidation state of the steel sheet surface by atmosphere control, etc., achieving stable coating adhesion.

The shapes of automotive components are diverse, and different formability, and particularly elongation and stretch flangeability, are required, depending on the component. Using various technologies, in 2017, JFE Steel established the high-formability JEFORMA™ series, which offers higher formability than general-purpose high-strength steel sheets. The recent lineup of the JEFORMA series is shown in **Table 1**. In the JEFORMA series, JFE supplies steel sheets with the necessary properties corresponding to the component. Using these technologies, JFE Steel and thyssenkrupp Steel Europe (tkSE) jointly developed the high-formability high-strength steel sheet jetQ™ to meet the needs of overseas customers, making it possible to supply galvanized steel sheets (GI) in Europe¹¹⁾.

2.2 Hot-Rolled High-Strength Steel Sheets

JFE Steel has established mass production of hot-rolled high-strength steel sheets up to the 980 MPa grade and is in the process of commercializing the 1 180 MPa grade.

As in the case of cold-rolled and GA high-strength steel sheets, microstructure control is essential because various properties other than strength are required in hot-rolled high-strength steel sheets. Hot-rolled steel sheets are rolled at a high speed of several 100 m/min or more at high temperatures exceeding 800°C, cooled to a specified temperature in the range of about 400°C to 600°C, and then coiled as products. When producing high-strength steel sheets, the thermal history must be

controlled with high accuracy during the short time of several seconds to several ten seconds from finishing to coiling to obtain a microstructure that displays the necessary properties. In particular, in order to manufacture high-formability high-strength steel sheets, it is important to form bainite, which is effective for achieving high strength and improving properties¹²⁾, and for this, it is necessary to cool the material with good accuracy to an appropriate temperature of 550°C or less. However, at temperatures under 550°C, it is known that the steam film which is formed on the steel sheet surface by water cooling easily becomes unstable, making precise temperature control difficult. Therefore, JFE Steel developed a cooling technology that also enables accurate cooling in this temperature region. Using this technology, JFE developed practical 780–980 MPa grade high-strength steel sheets with excellent stretch flangeability, and application is now expanding.

3. Application Technologies for Effective Use of High-Strength Steel Sheets

Application of high-strength materials to auto body frame components and chassis (suspension) parts is progressing with the aim of simultaneously achieving lightweighting and improved collision safety, and JFE Steel has also developed various application technologies for effectively using high-strength steel sheets. The following introduces a cold stamping technology for hard-to-form parts, welding technologies for improving the reliability and safety of the body and chassis, and a technology for evaluation of delayed fracture as an important issue for the 1 470 MPa grade steel sheets, which auto makers have begun to adopt recently.

3.1 Forming Technologies for Hard-to-Form Parts

In cold stamping of high-strength steel sheets, increased cracking, wrinkling and springback are major issues. For preliminary study of these problems, prediction and study of their causes by forming CAE analysis using the finite element method (FEM) is important.

JFE Steel developed a technology for predicting stretch flange failure and bending failure of the bend outer surface. These problems cannot be evaluated by the forming limit diagrams (FLD) which are widely used in crack prediction because the mechanisms that lead to cracking and fracture are different^{13,14)}. In springback prediction, high accuracy can be achieved by accurately expressing the stress-strain relationship of steel sheets at the bottom dead center (BDC) of press forming and when loading is removed. Therefore, the characteristics of unloading and reloading of high-

strength steel sheets in the uniaxial and biaxial stress states were investigated, a material model that reproduces the nonlinear stress-strain relationship on stress reversal in various deformation modes was proposed, and its effectiveness was demonstrated¹⁵⁾. For improvement of springback reduction, identifying the stress that becomes factor causing springback and countermeasures to reduce that stress is effective. Therefore, a springback root-cause analysis method for clarifying the root cause of springback was developed by relating the stress at BDC obtained by a press-forming CAE analysis to springback behavior¹⁶⁾.

In addition to these prediction and root-cause analysis technologies, countermeasure technologies for cracking, wrinkling and springback were also developed.

Since curved hard-to-form parts are susceptible to cracking and wrinkling, a preforming technology was developed by dividing the forming process into multiple stages, and designing the optimum geometry for the forming process before the final forming process.

When forming side-view curved parts, cracking and wrinkling caused by excess or insufficient material in the curved parts of the top and flanges are problems in conventional drawing. Inducing in-plane shear deformation in the vertical walls of the part is effective for preventing these problems. Therefore, JFE developed the “Shear Preforming Method,” in which deep-drawing of the rectangular blank is performed as the pre-forming process to introduce in-plane shear deformation in the region equivalent to the vertical walls, followed by bending of the bend line to the final part shape in the succeeding process. The effect of this method was verified with press-trial parts of 1 180 MPa grade material¹⁷⁾. As a further development of that technique, the “Twist Preforming Method” was also developed, focusing on the fact that in-plane shear deformation can be introduced by applying out-of-plane twist forming to the vertical walls of the part¹⁸⁾.

In forming of plan-view curved parts, on the other hand, stretch-flange deformation and compressive flange deformation occur in the flange, and cause of cracks and wrinkles. Dispersion of deformation can be expected if it is possible to promote material transfer at the punch top. Therefore, the “Large R Drawing Preforming Method” was developed to achieve the target geometry by enlarging the radius of the punch shoulder of the die in preforming to promote material flow, and then reforming the bend line. The effectiveness of this technique was demonstrated with an S-shaped trial part using a 1 180 MPa grade steel sheet¹⁹⁾. The “Large R Preforming Method” was also developed by applying this concept to forming, and its effect was verified with an L-shaped trial part using a 1 470 MPa grade steel

sheet²⁰⁾.

Springback is a type of deformation that occurs due to elastic recovery of the stress in a blank at the bottom dead center of forming, and the amount of springback increases in higher strength of steel sheets. Here as well, JFE Steel developed a technology that can control the stress that becomes a factor causing springback by dividing the forming process.

In side-view curved parts with a hat-shaped cross section, a type of springback called camber back is generated by the bending moment caused by the stress difference between the tensile stress of the punch top and the compressive stress of the flanges. As a method for reducing the stress of the punch top and flanges, JFE Steel developed the Stress ReverseTM utilizing the Bauschinger effect, whereby yield stress decreases when stress is reversed by slightly restoring strain²¹⁾.

In forming of plan-view curved parts with a hat-shaped cross section, twist springback, in which the part is twisted, occurs when the flange in-plane tensile and compressive stresses at the BDC are released upon tool release. As in the Stress ReverseTM JFE Steel developed a “Flange Position Control Method,” in which stress reversal by a slight restoration of strain is regarded as effective in reducing the flange stress that becomes a twist factor. After forming the top and vertical walls of the part, the flanges are formed while maintaining the top and walls in the formed condition²²⁾.

Among types of springback, wall warp (side wall curl) in the vertical walls of parts is also an issue. As the factor that causes wall curl, the moment in the curl direction generated in the steel sheet at the vertical wall position during forming remains until the BDC of forming. In this case, application of an inverse moment in the previous process to cancel out that moment is an effective countermeasure. To achieve this effect, JFE developed the “Wall Bending Preforming Method,” which consists of forming a bent shape in the vertical wall in the preforming process, followed by restriking in the final process²³⁾.

In recent years, the development of battery electric vehicles (BEVs) powered only by motors has continued to increase, but suppressing the large increase in vehicle weight and the rising manufacturing costs associated with the installation of large-scale batteries have become important challenges. Therefore, EV makers and part manufacturers are reviewing the vehicle structure and manufacturing process, focusing on reducing the number of parts by integration (one-piece design) of parts and functional integration. For this, JFE Steel is devoting great effort to the development of a part integration technology using cold stamping based the cold stamping technologies and structural design tech-

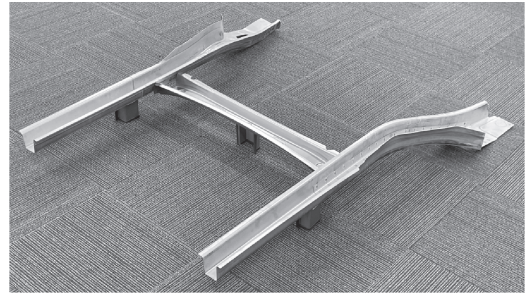


Photo 1 Prototype of rear member module integrated into three parts by cold press forming technology

nologies accumulated up to the present. In part integration of the rear module, JFE carried out technology development to reduce the original structure consisting of 11 parts to 3 parts by applying ultra-high-strength steel sheets up to 1 470 MPa grade. **Photo 1** shows an example of a pressed part that was actually manufactured using this technology⁴⁾. As a proprietary element technology for achieving this, JFE developed the “Cold Patchwork Method,” in which two overlapping blanks are formed into a one-piece modular structure after spot welding, and is also studying a preforming technology for preventing fracture of spot welds in the forming process²⁴⁾.

3.2 Welding Technologies for High-Strength Steel Sheets

Welding technologies which satisfy quality requirements are necessary and indispensable for increasing the degree of freedom in the application of high-strength steel sheets to automotive components. For example, in recent years, there have been increasing needs for part integration from the viewpoints of improving productivity and reducing manufacturing costs when manufacturing auto bodies. The main welding methods used in manufacture of the auto body structure are resistance spot welding, laser welding and gas-shielded arc welding. Using these welding methods with the proper materials at the proper places is essential for securing the quality of the welds⁴⁾. In recent years, the shapes of parts using high-strength steel sheets have become increasingly diverse, and the quality required in welds has become more advanced and complex. Until now, welding technologies have been developed to secure the strength properties of welded joints by preventing weld defects and ensuring a stable weld penetration shape. However, as additional requirements, in the resistance spot welds of high-strength steel sheets used in frame components, it is also necessary to prevent delayed fracture and liquid metal embrittlement (LME), and in gas-shielded arc welds of high-strength steel sheets used in suspension parts, corrosion resistance and fatigue fracture resistance must

be secured. The following sections introduce welding technologies developed by JFE Steel to satisfy these performance requirements for welded joints of vehicle bodies.

3.2.1 Welding Technologies for Vehicle Bodies

Application of high-strength steel sheets to automobile frame components is expanding, and it is necessary to secure high fracture strength not only in the base metal, but also in resistance spot welds. Therefore, JFE Steel developed “Pulse SpotTM Welding”^{25–32)}, which utilizes heat generation by a short time and high current pulsed post-current, as a proprietary welding technology that suppresses decreases in shear strength while improving the peel strength of resistance spot-welded joints. The short time and high current pulsed post-current method improves toughness by reducing segregation of phosphorus (P) in weld nuggets and relaxes stress concentration by a tempering effect.

Application of high-strength materials to corrosion-resistant frame components is also expanding, increasing the importance of resistance spot welding technologies for hot-dip Zn-coated high-strength steel sheets. One technical problem specific to resistance spot welding of hot-dip Zn-coated high-strength steel sheets is prevention of LME cracking in the heat affected zone (HAZ). As a new technology that secures high joint fracture strength while also suppressing LME cracking of the weld, JFE developed “J-NEKST SpotTM Welding Technology”^{33–35)}. This technology, which represents a further evolution and development of “Pulse Spot Welding,” is a revolutionary new welding technology that solidifies and detoxifies the Zn melted by the welding heat as a Fe-Zn alloy layer, and suppresses LME cracking by applying an appropriate thermal history to pulsed current heating in the corona bond, where LME cracking is a concern.

Further improvements in automobile collision performance and auto body rigidity are also strongly desired, and one effective measure for achieving these aims is increasing the number of resistance spot welds by shortening the interval between the weld spots. However, with conventional technologies, shunting of the current to previous weld spots becomes remarkable if the interval between the welds is extremely short, and stable nugget formation becomes impossible. To overcome this problem, JFE developed the “J-MAC SpotTM Welding Technology”^{36,37)}. With this technology, a uniform nugget diameter is secured, independent of the shunting condition and steel sheet strength, by performing heat control in which the adaptive control zone is divided into an optimized multistage current pattern.

3.2.2 Welding Technologies for Chassis Components

There are also strong needs for lightweighting in chassis components, and adoption of high-strength steel in those parts is progressing. The welded joints in chassis components are mainly lap fillet welded joints using gas-shielded arc welding. Since it is important to secure fatigue strength and corrosion resistance not only in the base metal, but also in the welded joints, JFE Steel developed the “Low CO₂ Gas-Shielded Arc Welding Technology”^{38–40)} with a substantially reduced CO₂ ratio in the shielding gas. With this technology, joint fatigue strength can be improved by expanding the radius of the weld toe, which is the origin of fatigue fracture⁴¹⁾.

In recent years, JFE Steel also developed “J-SKY MIGTM welding technology”^{42,43)} as a new gas-shielded arc welding technology assuming the high-strength steel sheets used in chassis parts. This technology is premised on MIG welding, in which pure Ar gas containing no CO₂ is used as the shielding gas. As a feature of the technology, metal transfer is stabilized by using a high-current pulse, resulting in the formation of a sound weld bead. In comparison with conventional welding, this technology dramatically reduces the amount of welding slag, which is effective for improving the corrosion resistance of joints.

As a technique for improving the fatigue characteristics of gas-shield arc welds, JFE developed the “Micro-Needle Peening Method”⁴⁴⁾, which improves the needle peening method, an established technology for bridges and other large-scale structures, so as to be suitable for automobile production lines. When applied to the weld toe, where fatigue cracks are a concern in chassis components, fatigue strength is greatly improved by applying compressive residual stress and forming a work-hardened layer by striking the weld toe with a pin with an optimized shape^{45,46)}.

3.3 Delayed Fracture Evaluation Technology

JFE Steel is devoting considerable effort to research and technology development to clarify the delayed fracture characteristics of sheared edges as a type of practical performance of high-strength steel sheets.

Considering factors extending as far as the automotive component production line, the effects of shearing conditions, the amount of forming strain of the sheared edge, and the effect of baking treatment were evaluated by respective tests^{47–49)}. JFE Steel developed a delayed fracture prediction method that combines this knowledge and forming CAE analysis, and verified its effectiveness with model parts applying 1 470 MPa grade steel sheets.

In order to estimate the delayed fracture characteristics of automobiles during actual use, JFE also developed HeTsACETM (Hydrogen embrittlement Test to simulate actual environment) as a cyclic test for evaluation of delayed fracture that simulates the hydrogen absorption condition under actual conditions. In this test, a specimen which has been deformed by bending loading and a hydrogen absorption monitoring system⁵⁰⁾ are placed in this environment. By comparison with the critical stress for delayed fracture with the maximum hydrogen uptake content, it is possible to quantitatively evaluate the use limits of materials from the view point of delayed fracture.

4. Conclusion

This paper has presented an overview of the high-performance automotive steel sheets and application technologies for achieving the full performance of those sheets which are distinctive features of JFE Steel. In view of the high needs for lightweighting of automobile bodies, application of high-strength steel sheets to automotive components is also expected to expand in the future. JFE Steel is promoting product development of high-performance, easy-to-use high-strength steel sheets, and is also devoting great effort to technology development to support automobile body design and manufacturing to contribute to the achievement of improved auto body performance and lightweighting.

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