

Mechanical Properties and Microstructure of Steel Sheets for Suppression of Fracture during Axial Crush and 980 MPa Galvannealed Steel Sheets with Excellent Fracture Resistance

YOSHIOKA Shimpei^{*1} KOMINE Shinsuke^{*2} SAKAIDANI Tomohiro^{*3}

Abstract:

Requirement for higher strength of parts that absorb energy at the collision, such as front side members, is rapidly increasing to reduce the weight of automobile bodies and to cope with the increase in vehicle weight due to the progress of electrification. However, fracture during axial crush which is a problem in over 980 MPa grade causes reduction and dispersion of the energy absorption of parts, and it is a bottleneck to increase the strength. From the axial crush test using 980 MPa grade steels with various chemical compositions and microstructures, it was found that the material design guideline to improve the hole expanding ratio (λ) is effective for stable axial crush without fracture. By the test simulating the deformation of the pre-bended portion, which is the fracture origin of the part, the basic analysis of the microstructure factor which affects the fracture was conducted, and the optimum microstructure design guideline was obtained. JEFORMATM 980GA-type2, which applies these findings, has excellent fracture resistance and enables stable energy absorption without fracture during axial crush.

1. Introduction

Auto makers are promoting high strength in automotive steel sheets to improve fuel economy by lightweighting the automobile body, and ultra-high-strength steel sheets with tensile strength (TS) of 1 470 MPa grade and higher have already reached practical application in non-deforming parts such as the cabin^{1,2)}. On the other hand, 440 to 780 MPa grade steel sheets are

mainly applied in energy absorption (EA) parts such as front side members and crash boxes, which are designed to absorb impact by deforming in a collision, but in response to the short-nose designs of electric vehicles (EVs) and increased weight accompanying electrification in recent years, needs for high-strength steel sheets in EA parts are also increasing rapidly.

However, parts using steel sheets with 980 MPa grade and higher strength may sometimes fracture without undergoing accordion-like crush deformation (compact mode deformation) during axial crushes. Fracture during crushing destabilizes the deformation mode of the part as a whole, and causes an increase in the variation of EA, in other words, a decrease in robustness^{3,4)}. Since this is a fatal issue which is directly related to the reliability of structural parts, fracture resistance during axial crush is extremely important when developing ultra-high-strength steel sheets for EA parts assuming strength up to 1 470 MPa. Although this is a new property that has not received attention until now, material design guidelines for improvement of this property are needed.

In the past, it was suggested that fracture during axial crush deformation tends to be suppressed in materials with excellent bendability and stretch-flangeability⁵⁻⁹⁾. However, only limited types of steel sheets have been investigated, and the microstructural mechanism of fracture suppression is also unclear due to the complex deformation of parts during axial crush, and the difficulty of identifying the material-related factors that affect fracture behavior during axial crush.

This paper describes the advantageous properties of

^{*} Originally published in *JFE GIHO* No. 57 (Feb. 2026), p. 14–20

^{*1} Senior Management Researcher, Sheet Products Research Dept., Steel Res. Lab., JFE Steel

^{*2} Senior Researcher, Joining & Strength Research Dept., Steel Res. Lab., JFE Steel

^{*3} Senior Researcher, Forming Technology Research Dept., Steel Res. Lab., JFE Steel

steel sheets for suppression of fracture during axial crush, which were determined through axial crush tests of various types of steel sheets, and efforts to clarify the effects of the material microstructure on crack initiation and crack propagation behavior by a new material test which fundamentally simulates the deformation history at the fracture initiation site^{10–12}. In addition, a 980 MPa grade galvannealed steel sheet (GA; JEFORMATM 980GA-type2), which reflects the material design guideline obtained through this study, is also introduced.

2. Steel Sheet Properties Necessary for Suppression of Fracture during Axial Crush

2.1 Experimental Method

In order to clarify the effects of steel sheet properties on the fracture phenomena that occur during axial crush, in this study, we examined 15 types of 980 MPa grade steel (thickness: 1.2 mm) with different mechanical properties due to differences in the steel composition and microstructure. Steels with a wide variety of microstructures were used, including dual-phase (DP) steels consisting of ferrite and martensite phases, multi-phase microstructures containing retained austenite (γ) and bainite, and a single-phase martensitic microstructure. The specimens used in the axial crush test were first bent to the hat-shaped cross section shown in **Fig. 1** (a), after which a flat sheet of the same steel was prepared as a back sheet, and the flange part was spot-welded at an interval of 45 mm. **Fig. 1** (b) shows the typical appearance of a specimen before and after the test. The tests were performed using a precision universal testing machine manufactured by Shimadzu Corporation, and the specimens were crushed to a stroke of 100 mm at a speed of 0.17 mm/s. The tests were performed 3 times with each steel, and their fracture

behavior was analyzed.

The hole expanding ratio λ conformed to the standard JIS Z 2256, and the die diameter used in punching was 10.3 mm (clearance: 12.5%). Bendability was evaluated by two methods. In order to evaluate the occurrence tendency of comparatively fine cracks, a 90° V bending test was carried out by the V-block method in accordance with JIS Z 2248. In this test, the limit bending radius R was defined as the smallest die radius at which cracking did not occur at the bend apex when a strip specimen was bent, and R divided by the sheet thickness t (i.e., R/t) was used as an index. The second method used here was the bending test¹³) (hereinafter, VDA bending) standardized in VDA238–100 (2017) for evaluation of the crack behavior of members during crushing in the standards of the German Association of the Automotive Industry (VDA: Verband der Automobilindustrie). Bending was performed in accordance with the VDA standard, and the bending angle α on reaching the maximum load was used as an index. In both 90°V bending and VDA bending, the bending direction was set so that the rolling direction of the steel sheet was parallel to the bend line.

2.2 Deformation/Fracture Modes during Axial Crush

Based on time-series observation of the axial crush behavior of the 980 MPa grade steels with different steel sheet properties, the fracture modes could be broadly classified into 3 types. **Figure 2** shows typical examples. **Fig. 2** (a) is an example of crush deformation in the compact mode without fracture. In this deformation mode, the deformation load is maintained stably until a high stroke, while repeatedly showing maximum and minimum values due to continuous buckling. Therefore, this is the ideal deformation mode for stably obtaining absorbed energy^{14,15}. **Fig. 2** (b) is an example in which crush deformation in the compact mode occurred in part of the specimen, but fracture was also observed, and (c) is an example in which fracture initiated during buckling in the initial stage, and was followed by splitting of the flat sheet with no new buckling. **Fig. 2** (c) is the worst-case deformation mode. However, partial fracture also occurred in (b), and (b)

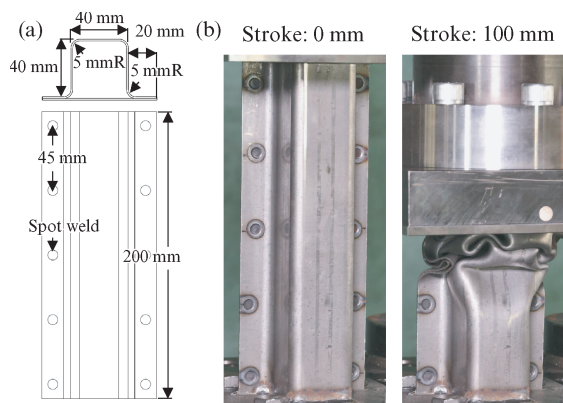


Fig. 1 (a) Specimen used for axial crush test and (b) typical appearance of tested specimen

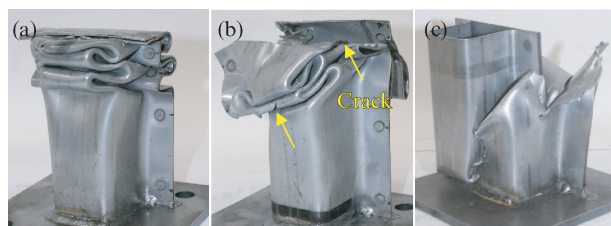


Fig. 2 Typical appearance of fracture mode

showed varying results in the 3 tests, as fracture occurred in some but not all cases. These results indicate that the compact mode in (a) must be achieved stably in order to stabilize EA at a high level.

2.3 Relationship of Fracture Resistance and Steel Sheet Properties

To analyze the effect of steel sheet properties on the above-mentioned occurrence tendency of the deformation modes during axial crush, scores of 1, 0.5 and 0 were assigned to fracture modes in Fig. 2 (a), (b) and (c), respectively, and the total score for 3 trials was defined as the Crush Fracture Index (CFI), which was used as an index of fracture resistance. **Figure 3** shows the correlation of CFI and various mechanical properties. In addition to the properties of elongation (El) and the hole expanding ratio λ , which are generally used as indices of the formability of automotive steel sheets, this figure also shows the correlation with bendability because the buckled region in axial crush parts displays the bending deformation mode. The sufficient condition of steel sheet properties for obtaining a stable deformation mode (CFI = 3) with no occurrence of fracture is considered to change depending on the conditions of the axial crush test. However, in this study, this condition was as shown by the solid vertical lines in the figures. Among the properties, λ showed a strong correlation with fracture resistance, as CFI = 3 when λ was 45% or more. Although there was also a type of steel that achieved CFI = 3 when λ was approximately 25%, this case was limited to only 1 steel type among the steels that achieved CFI = 3. Sufficient conditions for CFI = 3 could be seen in the 90°V bending and

VDA bending (α) properties, but the correlation of these properties was considered to be relatively weak because 5 steels and 4 steels, respectively, achieved CFI = 3 without meeting the sufficient conditions for 90°V bending and VDA bending.

Figure 4 shows examples of detailed observation of the deformation and fracture initiation site during axial crush. A black line was drawn in advance on the bend line of bending during specimen preparation. Focusing on the region where deformation progressed, resulting in buckling, after flattening of the bend line part, the specimen was bent in the opposite direction at the stroke of 20 mm so as to be perpendicular to the original bend line, and fracture occurred. In other words, the fracture initiation site was in the pre-bent region, and the fracture mode was different from 90°V bending or VDA bending.

These results suggested that improvement of the deformation properties (formability) of the pre-bent region is effective for suppression of fracture during axial crush. Since λ , which showed a strong correlation

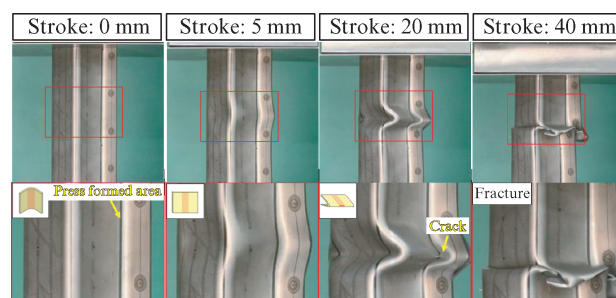


Fig. 4 Deformation and fracture behavior during axial crush

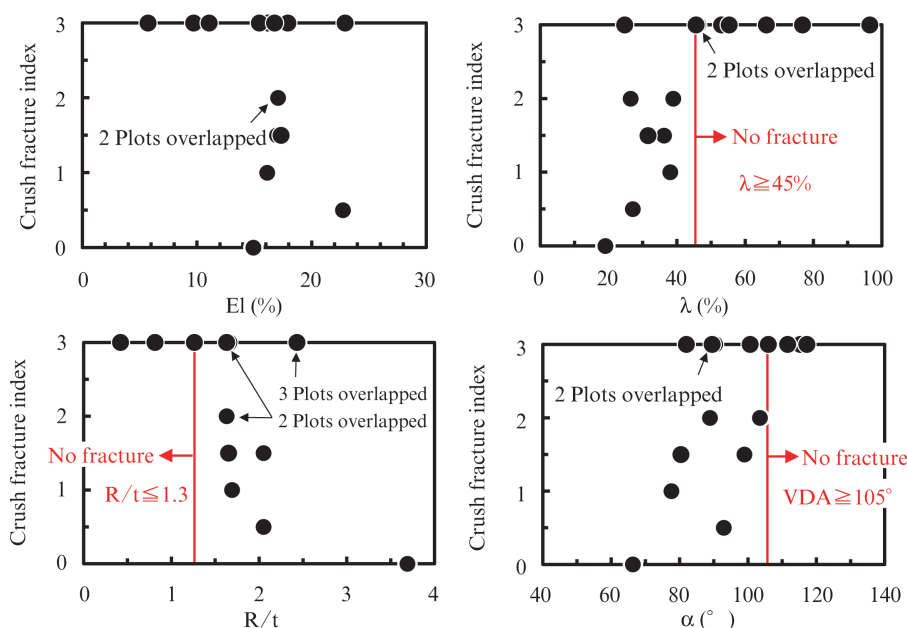


Fig. 3 Relationship between mechanical properties and crush fracture index

with fracture resistance in the axial crush test, is an index for evaluating the deformation properties of the edge of materials subjected to pre-shear working, it can be thought that there is some microstructural factor that has a common effect on both improvement of λ and fracture resistance.

3. Controlling Factor of Fracture Resistance in the Pre-Bent Region

3.1 Experimental Method

To fundamentally clarify the microstructural factor that controls the fracture resistance of the pre-bent region, 900 MPa grade model steels with different mechanical properties were prepared in the laboratory and evaluated by a fundamental test simulating fracture of the pre-bent region^{10–12)}. The microstructures and mechanical properties of the specimen steels are shown in Fig. 5 and Table 1, respectively. The low λ steel in Fig. 5 (a) has a DP microstructure, and the high λ steel in Fig. 5 (b) has a multiphase microstructure that includes intermediate-hardness phases such as tempered martensite and bainite, as well as a small amount of retained austenite (retained γ). The high EI steel in

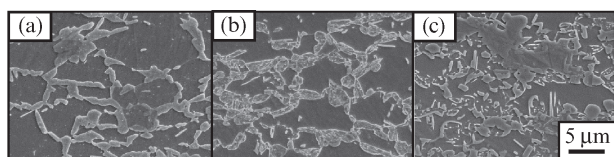


Fig. 5 Microstructure of (a) low λ , (b) high λ , (c) high EI steel

Table 1 Mechanical properties of steel

Steel	Thickness (mm)	YS (MPa)	TS (MPa)	EI (%)	λ (%)
Low λ	1.2	446	925	19	20
High λ	1.2	682	923	21	70
High EI	1.2	509	905	30	33

Fig. 5 (c) is a TRIP (TRansformation-Induced Plasticity) steel containing bainite, martensite and retained γ . Here, the martensite included in the low λ steel and the high EI steel is hard martensite that has not undergone tempering (hereinafter, fresh martensite).

Figure 6 shows a schematic image of the bending test (hereinafter, V-VDA bending test) simulating the fracture initiation site during the axial crush test observed in Fig. 4. The bend line in press forming was simulated by pre-bending the specimen using a 90°V-block with a die radius of 5 mm. Next, bending deformation was performed in the opposite direction under conditions conforming to VDA238–100, as shown in Fig. 6 (a) so that the bend line was perpendicular. Fig. 6 (b) shows a schematic image of the stroke-load curve under reverse bending. Assuming the stroke when the pre-bent specimen was flattened by reverse bending is the starting point (0 mm), the stroke at maximum load was defined as S_{Fmax} and was used as an index of fracture resistance. For comparison, the VDA bending test was also performed. In order to evaluate the crack initiation and propagation behavior before and after maximum load, both tests were interrupted while in progress, and the sheet thickness cross section perpendicular to the bend line was observed. The ratio of the crack depth to the sheet thickness was obtained, and in addition to calculation of the crack growth ratio, the void formation behavior was also analyzed.

3.2 Fracture Behavior in V-VDA Bending Test

Figure 7 shows the stroke-load curves in the VDA bending and V-VDA bending tests. In the low λ steel and high EI steel, a rapid decrease in load due to fracture in the pre-bent region was observed in the V-VDA bending test, resulting in discontinuous stroke-load curves. Figure 8 shows the S_{Fmax} in the respective bending tests. The rapid load decrease occurred at a lower stroke in the V-VDA bending test than in the VDA bending test, implying that fracture was accelerated by pre-bending. The decrease in S_{Fmax} due to pre-bending was large in the low λ and high EI steels, and small in the high λ steel.

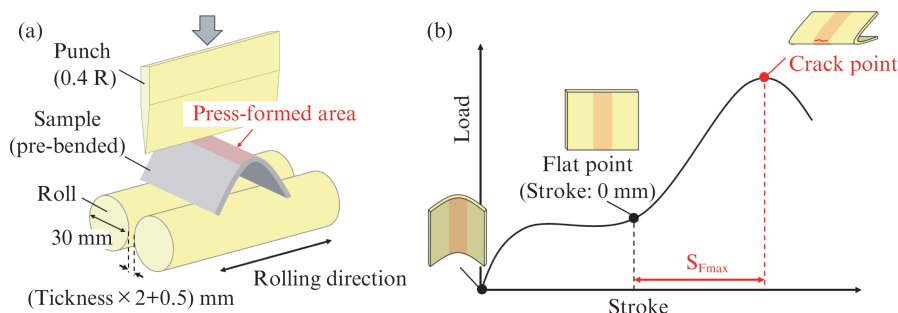


Fig. 6 Schematic image of (a) V-VDA bending and (b) stroke-load curve

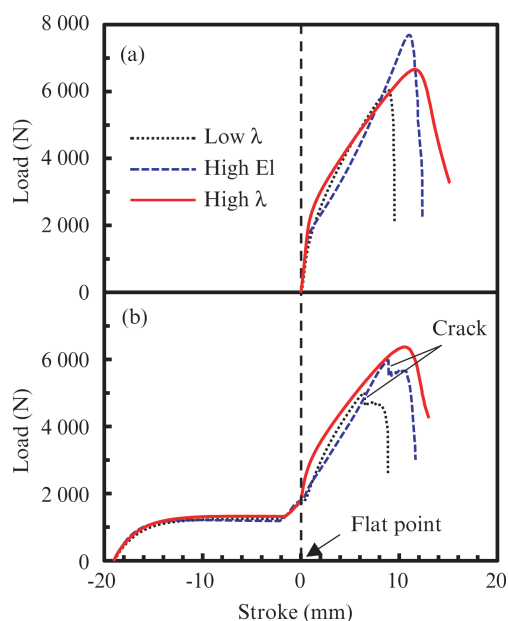


Fig. 7 Stroke-load curve for (a) VDA bending and (b) V-VDA bending test

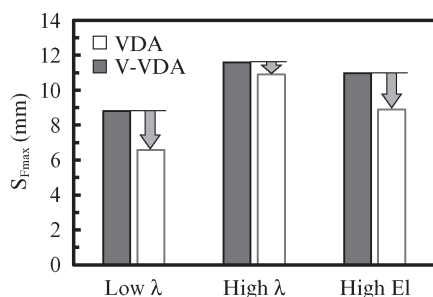


Fig. 8 S_{Fmax} of VDA bending test and V-VDA bending test

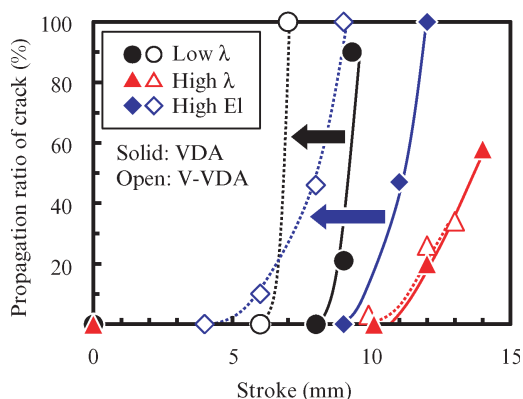


Fig. 9 Crack growth behavior in VDA bending test and V-VDA bending test

Figure 9 shows the crack growth ratios in each test. Regarding the crack growth behavior, in the VDA bending without pre-bending, no remarkable differences could be seen in the stroke at fracture of the vari-

ous steels. However, in the V-VDA bending with pre-bending, the stroke at fracture was smaller, and there were also differences among the steels. In particular, the effect of pre-bending on the high λ steel was extremely small.

Based on these points, in order to suppress fracture of axial crush specimens, it is important to suppress initiation of cracks in the bend line region, which is the fracture initiation site, and although crack initiation is accelerated by pre-bending, these tests revealed that the effect of pre-bending can be reduced by high λ material.

3.3 Microscopic Deformation Behavior in the Pre-Bent Region

To elucidate the mechanism of the reduced effect of pre-bending seen with the high λ material, the elementary process of crack initiation in the region subjected to pre-bending was observed. The observed microstructure was the surface layer on the bending tension side during the V-VDA bending test (i.e., the bending compression side during pre-bending). **Figure 10** shows

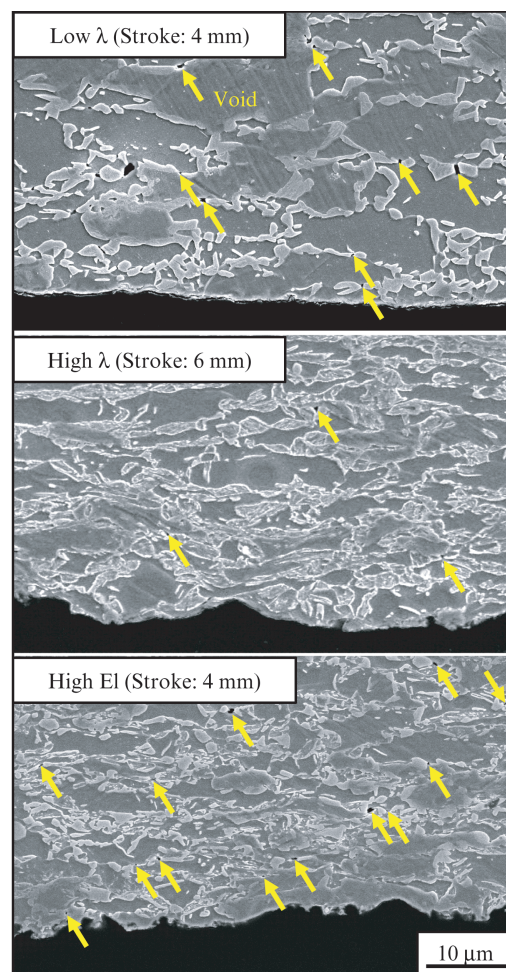


Fig. 10 Microstructure of the bending surface at beginning of V-VDA bending test

microstructural images when the test was stopped at a stroke before crack initiation. Focusing on the void formation positions, in all cases, voids had formed at the martensite interface. Comparatively coarse voids also existed in the low λ steel, mainly at the coarse martensite interface. This suggested the possibility that the grain diameter of the hard phase, which becomes the site of void formation, affects the diameter of the formed voids. **Figure 11** shows histograms of the number density relative to the void diameter in the surface layer on the bending tension side (bending compression side in pre-bending) in the initial period of void formation (stroke: 4–6 mm). The number density of all voids was remarkably small in the high λ steel, and was roughly similar in the low λ steel and high EI steel. This difference is thought to occur because the use of tempered martensite in the high λ material reduced the region where large hardness differences exist, reducing the strain concentrations at the phase interface during bending compression. Regarding the void diameter, in the low λ steel, it was found that relatively coarse voids with diameters of 0.5 to 1.2 μm made up about 30% of the total, even in the initial period of void formation. **Figure 12** shows the relationship of the average grain diameter of the fresh martensite and retained γ , and the average void diameter. As the average grain diameter of the fresh martensite or retained γ decreased, the average void diameter of the voids that form near fresh martensite or retained γ also tended to be small.

From the above, in order to reduce the effect of pre-bending and suppress fracture during axial crush, these results clarified the fact that reducing the hardness difference at the phase interface by utilizing intermediate-hardness phases such as tempered martensite

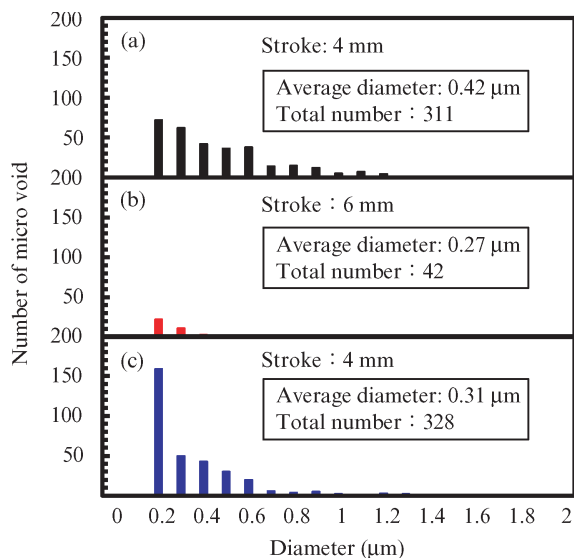


Fig. 11 Void analysis result for V-VDA bending sample of (a) low λ steel, (b) high λ steel, (c) high EI steel

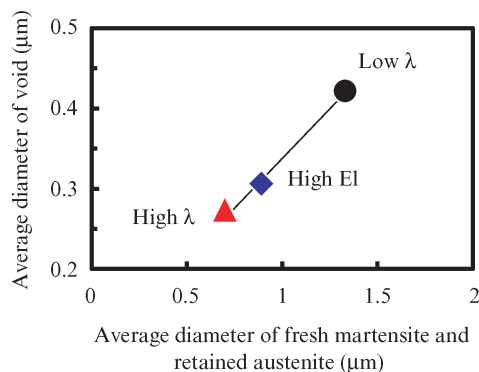


Fig. 12 Effect of diameter of fresh martensite and retained austenite on void diameter

or bainite, and fine dispersion of hard phases by a multiphase microstructure design is an effective microstructure control guideline. Although it has long been known that this type of microstructure control is effective for improving the hole expanding property λ , this study made it clear that it is also effective for suppressing cracks that initiate during orthogonal reverse-bending deformation of the pre-bent region, which becomes the fracture initiation site in axial crush, and thus clarified the design principle for suppressing fracture in axial crush, which had been unclear until now due to the complexity of the fracture phenomena.

4. Features of 980 MPa Grade GA High-Strength Steel Sheet for EA Parts

As a JFE Steel product that reflects the design principle for improvement of fracture resistance described in this paper, this chapter introduces JEFORMA™ 980GA-type2¹⁶⁾ (980 MPa grade GA high-strength steel sheet), which contributes to high strength and thickness reduction of parts in which stable energy absorption in collisions and corrosion resistance are required, such as front side members and crash boxes. **Table 2** shows the mechanical properties of JEFORMA 980GA-type2 and a general-purpose 980GA high-strength steel sheet. From the viewpoints of suppressing fracture during collisions and securing the robustness of the energy-absorption (EA) amount, JEFORMA 980GA-type2 has a λ of 60%. It is thought that its excellent λ and high

Table 2 Mechanical properties of 980 MPa grade GA steel sheet

Steel	YS (MPa)	TS (MPa)	EI (%)	λ (%)
JEFORMA™ 980GA-type2 (Developed)	850	1 030	15	60
Conventional 980GA	630	1 030	14	25

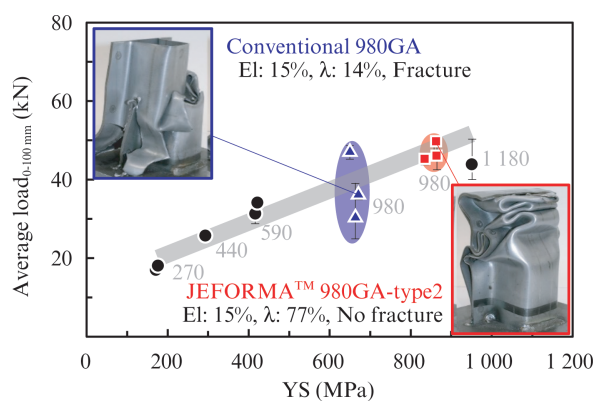


Fig. 13 Average load in axial crush test of developed steel

El, which is comparable to that of the conventional steel, will enable easy press forming of EA parts. A pillar lowers and other parts in which stretch-flange cracking is a concern, contributing to expansion of the types of applicable parts and the degree of freedom in shape design. In addition, reduction of the soft phase for the high λ design also results in a remarkable improvement of yield strength (YS), which increases buckling strength in axial crush and contributes to improvement of EA amount^{17,18)}.

Figure 13 shows the results of an axial crush test of JEFORMA 980GA-type2 and a conventional 980GA high-strength steel sheet. The test method was the same as that described in Chapter 2, and the average load of a stroke of 0 to 100 mm was arranged by YS. For comparison, the figure also shows the results for strength classes other than the 980 MPa grade. With the conventional 980GA high-strength steel sheet, there are cases where fracture occurs during axial crush, and variations in the average load are large. In contrast, since the JEFORMA 980GA-type2 displays crush deformation in the compact mode, stable average values at a high level were confirmed.

5. Conclusion

For fracture during axial crush, which was a challenge for the application of high-strength steel sheets to energy-absorbing parts, JFE Steel developed a 980 MPa grade high-strength steel sheet for EA parts by clarifying the relationship between the elementary process of fracture and microstructural factors. The knowledge gained in this study is also being used in the development of 1 180 and 1 470 MPa grade ultra-high-strength steel sheets. Since there are still large challenges for practical application of those products in terms of formability, weldability, delayed fracture, etc., JFE Steel is also developing solution technologies that respond to those issues, while contributing to further

improvement of automobile structural performance through conversations with customers.

References

- 1) Yoshioka, S.; Ono, Y.; Funakawa, Y. 1.5GPa Grade Cold-rolled Steel Sheets for Automotive Parts with Excellent Energy-saving Effect and Crashworthiness. *Energies*. 2018, vol. 97, no. 3, p. 244–247.
- 2) Kimura, H.; Okubo, T.; Shinmiya, T. Advanced Steel Materials and its Application Technology Contributes to Automotive Innovation. *Bulletin of the Iron and Steel Institute of Japan*. 2022, vol. 27, no. 1, p. 15–20.
- 3) Maki, H.; Takaki, N. Mechanical Properties and Collision Deformation Performance of 980 MPa-grade High-Strength Steel Sheet. *SAE International Journal of Materials and Manufacturing*. 2018, no. 2018-01-0624, p. 1–8.
- 4) Tanaka, Y.; Miyata, K.; Tasaka, M.; Nakazawa, Y.; Tomida, T. Effect of Cross Sectional Shape and Material Properties on Impact Deformation Behavior of Ultra High Strength Steel Members. *Transactions of the Japan Society of Mechanical Engineers, Series A*. 2012, vol. 78, no. 791, p. 955–965.
- 5) Maki, H.; Takaki, N. Application of Next-generation High-lambda-type High-strength Steel Sheets. *Transactions of the Society of Automotive Engineers of Japan*. 2017, vol. 48, no. 6, p. 1347–1352.
- 6) Okitsu, Y.; Takagi, S.; Tamai, Y.; Naito, T.; Okuda, K.; Takaki, N.; Sugiura, T. Effects of Mechanical Properties of Steels on Dynamic Collapse Behavior of High Strength Steel Hat Columns. *Journal of the JSTP*. 2019, vol. 60, no. 700, p. 123–129.
- 7) Okitsu, Y.; Takagi, S.; Tamai, Y.; Naito, T.; Okuda, K.; Takaki, N.; Sugiura, T. Effects of Mechanical Properties of Steels on Dynamic Collapse Behavior of High Strength Steel Hat Columns. *Materials Transactions*. 2022, vol. 63, no. 2, p. 232–239.
- 8) Nakaya, M.; Kanetada, S.; Tsunazawa, M. Hot-dip Galvannealed Steel Sheet of 980 MPa Grade Having Excellent Deformability in Axial Crush. *R&D Kobe Steel Engineering Reports*. 2019, vol. 69, no. 1, p. 25–28.
- 9) Sato, K.; Sakaidani, T.; Toji, Y.; Takajo, S.; Paton, A.; Irnich, M.; Thiessen, R. Effect of Local Ductility of Advanced High Strength Steels in 980 MPa and 1180 MPa Grades on Crash Performance of Automotive Structures. *SAE International Journal of Advances and Current Practices in Mobility*. 2024, vol. 6, no. 1, p. 278–287.
- 10) Komine, S.; Nakagaito, T.; Yokota, T.; Sakaidani, T.; Sato, K.; Urabe, T. Effect of Microstructural Factors and Mechanical Properties on Axial Crash Fracture of High Strength Steel Sheets. *Transactions of the Society of Automotive Engineers of Japan*. 2021, vol. 52, no. 1, p. 94–99.
- 11) Sakaidani, T.; Sato, K.; Tamai, Y.; Komine, S.; Nakagaito, T.; Urabe, T. Axial Crash Fracture of 980 MPa High Strength Steel Sheets. *Transactions of the Society of Automotive Engineers of Japan*. 2021, vol. 52, no. 1, p. 197–202.
- 12) Komine, S.; Nakagaito, T.; Kaneko, S.; Toji, Y.; Sakaidani, T.; Sato, K. Mechanical Properties and Microstructure of High Strength Steel for Fracture Suppression and High Absorbed Energy in Automobile Collision. *Tetsu-to-Hagané*. 2025, vol. 111, no. 9, p. 514–525.
- 13) VDA. VDA 238–100: 2017. Plate Bending Test for Metallic Materials. 2017.
- 14) Toda, K.; Gondoh, H.; Takechi, H.; Usuda, M. Absorbed energy during compression and crushing of high strength steel sheets. *Metallurgical Transactions A*. 1976, vol. 7, no. 11, p. 1637–1642.
- 15) Yamashita, M.; Goto, M.; Takahashi, T.; Sawairi, Y. Axial Crush of Strengthening Structural Members with Various Hat-Shaped Cross-Sections. 1st Report, Impact Test by a Drop Hammer. *Transactions of the Japan Society of Mechanical Engineers, Series A*. 2002, vol. 68, no. 668, p. 668–673.
- 16) Minami, H.; Kobayashi, T.; Funakawa, Y. Cold-rolled and Galvannealed (GA) Ultra High Strength Steel Sheets for Automobile

[Structural Parts. JFE GIHO. 2018, no. 41, p. 20–27.](#)

- 17) Takaki, S.; Iizuka, E.; Miura, K.; Furukimi, O.; Tanimura, S. Effect of strain rate on the strength of steel sheet. Current Advances in Materials and Processes (Proceedings of the ISIJ). 1996, vol. 9, no. 3, p. 532.
- 18) Uenishi, A.; Suehiro, M.; Kuriyama, Y.; Usuda, M. Mechanical properties at high strain rate and impact energy absorption of high strength steel sheets. Current Advances in Materials and Processes (Proceedings of the ISIJ). 1996, vol. 9, no. 5–6, p. 1114.