

Comparative Investigation of the Stretch-flange Cracking Mechanism of Ultrahigh-strength Steels with Different Microstructures and Hole-Expansion Ratios

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Summary: Ultrahigh-strength steel sheets (UHSSs) have been widely adopted for reducing the weight of auto mobile body structures in order to combine fuel efficiency with crashworthiness. One of the issues in the press forming of UHSSs is to prevent stretch-flange cracking on the sheared edges of blank sheets. Although countermeasures have been developed in terms of both materials and processes, the fundamental picture of stretch-flange cracking in diverse types of UHSSs was unclear. In this study, we investigated the mechanism and material factors of stretch-flange cracking in UHSSs with a tensile strength of 980 MPa grade, comparing dual phase(DP), transformation induced plasticity(TRIP) and full martensite(FM) microstructures. The material sheets were pierced by punching or machining, and subsequently, hole-expansion-tested and observed. Macroscopic observation in the tests revealed that

the hole-expansion limit was determined by the earliness of crack propagation relative to the hole-expansion ratio. Scanning electron microscope (SEM) analysis of the expanded edge interior showed that void formation occurred exclusively around the crack tip area, thus contributing to ductile crack growth. Microscopy analysis of the expanded edge surfaces revealed the details of stretch-flange cracking. The analysis results suggested that the flange cracks more easily proceeded and cleaved in the order of TRIP, DP, and FM. It was concluded that the crack growth behavior and the hole-expansion limit were dominated by the microstructural resistance to crack growth generated from work-hardened layer.

Key words: ultrahigh-strength steel sheets, sheared edge, stretch-flangeability, microstructure, fracture.

1. Introduction

As CO₂ emission reduction becomes a global consensus, the reduction of automobile body weight is required to improve the fuel efficiency and driving range of electric cars. On the other hand, crash safety standards have been enhanced. To satisfy both needs, there is a trend to increase the strength of automobile frame components[1,2]. Hot stamping and the cold-press forming of ultrahigh-strength steel sheets (UHSSs) are used to produce high-strength frame components. Cold-press forming has been mainly used in Japan because of its high productivity; however, press-

forming defects such as cracking and dimensional accuracy defects due to the decreased formability of UHSSs have become problems.

One of the issues in the cold-press forming of UHSSs is stretch-flange cracking on the sheared edge surface induced by punching, along with the tensile deformation during the subsequent forming of UHSSs. The hole-expansion limit λ obtained from the hole-expansion tests in accordance with International Organization for Standardization (ISO) standards is generally used as an indicator of the stretch-flangeability of materials. According to previous reports, the influencing factors for the decrease in λ related to machining techniques were the significant work-hardening of the sheared edge surface[3-9] and the high roughness of the edge surface[7,9-11]. The influencing factors for the decrease in λ related to microstructures were the high heterogeneity due to the hardness difference between soft and hard phases in the microstructure[3,4,12-18], the low fracture toughness, which represents the resistance to crack formation and propagation[19-22], and the low local ductility[9,23].

Different types of UHSSs, such as dual-phase (DP) steel, transformation-induced-plasticity (TRIP) steel, and full-martensite (FM) steel, have been developed and used for automobile components. Each type of steel has its unique mechanical properties, including stretch-flangeability, depending on its

microstructure. DP steel has excellent strength-ductility balance because of the two-phase microstructure consisting of a soft phase (ferrite) and a hard phase (martensite). However, the stretch-flangeability of DP steel tends to decrease as its strength increases owing to the increasing hardness difference between the soft and hard phases[1,2,12-14]. TRIP steel has a composite microstructure containing retained austenite and has excellent ductility resulting from the work-hardening caused by stress-induced phase transformation[24]. However, the stretch-flangeability of TRIP steel decreases rapidly because of the presence of the retained austenite phase[25]. FM steel is composed of a single phase of hard martensite with high strength and low ductility. However, because of its fine and homogeneous microstructure, FM steel shows excellent stretch-flangeability when it is tempered to soften the microstructure[26-28]. The improvement of the stretch-flangeability of those steels is an important development issue.

While the dominant mechanical factors of stretch-flangeability[29] and the fracture states of DP and martensite (MS) steels with different strengths[30] have been investigated, the microbehavior of the fractures occurring and propagating during stretch-flange deformation and the detailed mechanism of a work-hardened layer inducing stretch-flange cracking have remained unclarified. Also, the influencing factors of stretch-flangeability related to the

difference in the types of steel, such as DP, TRIP, and MS steels, and their relationship with the fracture mechanism have not been clarified in previous studies.

In this study, the UHSSs made of DP, TRIP, and FM steels with a tensile strength of 980 MPa grade were used to investigate the fracture behavior of stretch-flange cracking caused by the formation and propagation of cracks. First, the macro-fracture behavior in different types of steel and its effects on the hole-expansion limit were examined. Second, the behaviors of voids and the work-hardened layer in fractures were examined. Lastly, the material factor affecting the stretch-flangeability was discussed in terms of the differences in crack propagation behavior among different types of steel.

2. Experimental methods and conditions

2.1 Sample materials

Cold-rolled nonplated DP steel, TRIP steel, and FM steel with a tensile strength of 980 MPa grade (hereinafter referred to as "980DP", "980TRIP", and "980FM", respectively) having the mechanical properties shown in Table 1 were used in this study. In Table 1, U.El and T.El refer to uniform elongation and total elongation, respectively. The mechanical properties were determined as the mean values of results obtained in two tensile tests performed on JIS5 tensile test specimens in the rolling

direction. The hole-expansion limit λ (%) in Table 1 was determined as the mean value of the results of four hole-expansion tests performed on punched holes in accordance with JIS Z 2256.

Table1. Mechanical properties of cold-rolled test specimens

Steel type	YS /MPa	TS /MPa	U.El /%	T.El /%	Thickness /mm	λ /%
DP	771	1009	7.0	15.5	1.4	41
TRIP	662	1030	16.7	24.6	1.2	26
FM	957	1035	3.4	6.2	1.2	74

DP steel had a two-phase microstructure consisting of ferrite and martensite phases, TRIP steel had a composite microstructure containing ferrite, bainite, and retained austenite phases, and FM steel had a single-phase microstructure consisting of a tempered martensite phase. Figure 1 shows the scanning electron microscopy (SEM) images of nital-etched microstructures of the steels. The bright areas are martensite and retained austenite regions that were not easily etched, whereas the dark areas are easily etched ferrite and bainite regions.

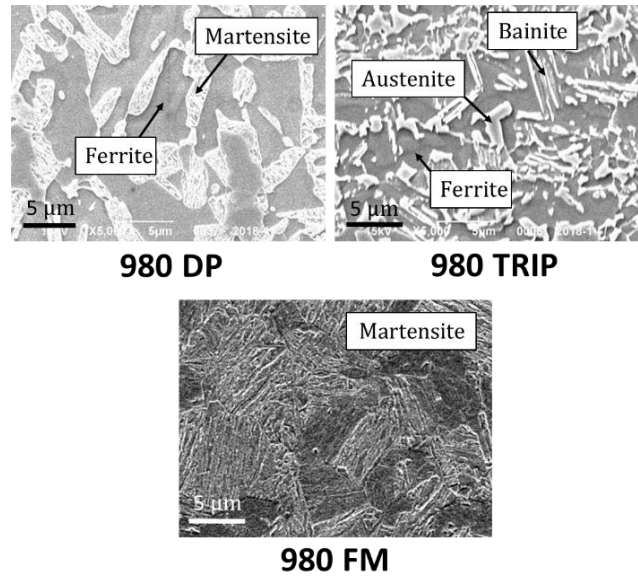


Fig. 1 SEM images of the microstructures of the test specimens

2.2 Piercing

The edge surfaces subjected to the hole-expansion tests were prepared by punching or by machining and reaming of a circular hole around the center of the specimens cut to the size of 100 × 100 mm². The purpose of this process was to determine the effects of the work-hardened layer in the cracked edge surface through a control experiment in which the punched holes having a work-hardened layer and machined holes less affected by work-hardening were compared. The one-side clearance of the punching tool was maintained constant at 12% of the sheet thickness.

2.3 Hole-expansion tests

Figure 2 shows a schematic of the hole-expansion test setup. Hole-expansion tests (JIS Z 2256) were performed on specimens with punched or machined holes with a diameter of $\Phi_B = 10$ mm using a punch with an apex angle of $\theta_P = 60^\circ$ and a diameter of $\Phi_P = 50$ mm, which are the most common conditions of hole-expansion tests. The bead diameter of the blank holder was 80 mm. Those specimens were used in the observation described later. The tests on punched holes were performed in the direction in which the punch did not come into contact with burrs. Stretch-flange cracking was identified when a crack detectable by the naked eye penetrated the sheet thickness. The hole-expansion limit λ was defined as the rate of increase in the pierced hole diameter at the time when stretch-flange cracking was identified compared with the initial hole diameter.

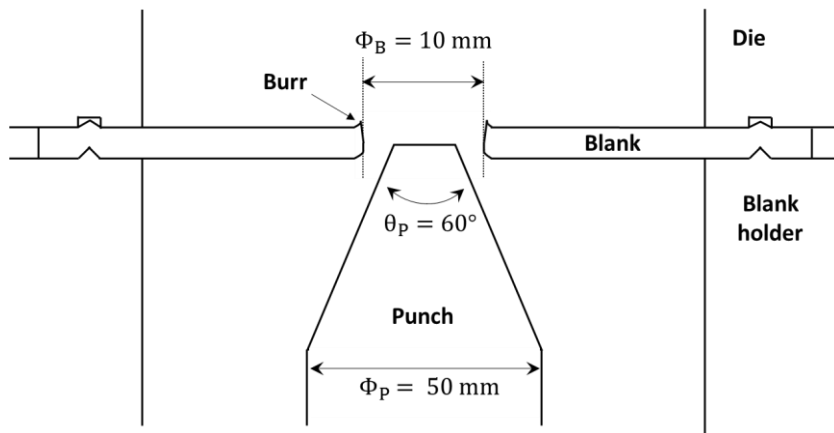


Fig. 2 Schematic of the hole-expansion tests setup

2.4 Observation of test specimens

A sample for each observation condition was prepared from the hole-expansion test specimens and subjected to the following observations.

- 1) Video recording of pierced edge surface during hole expansion
- 2) SEM observation of vertical section of pierced edge surface before and after hole expansion
- 3) Microscope observation of pierced edge surface before, during, and after hole expansion

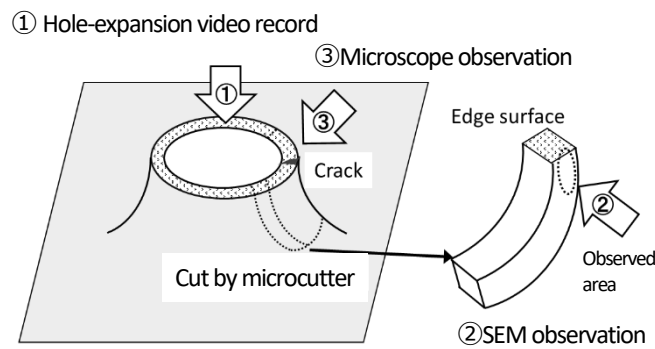


Fig. 3 Schematic of the tests and observations

Figure 3 shows the test specimen shape and a schematic of tests and observations.

In 1), a video of the pierced edge surface was recorded from vertically above the sheet surface while the hole-expansion test was performed by uplifting the punch at a constant rate. The hole diameter was measured at the same time. Samples in which hole

expansion was stopped before a crack penetrated the sheet thickness were prepared.

In 2), the samples before and after hole expansion were subjected to SEM observation. The samples were cut from the test specimens in the vertical direction of the sheet using a microcutter. The areas with no cracks penetrating the sheet thickness were selected in order to avoid the specific effects of such cracks on their surrounding areas. The samples were mirror-polished, etched in nital solution, and subjected to the observation of the microstructure near the pierced edge surface of the vertical section. After that, the samples were mirror-polished again, but not etched, and observed to determine the number density and the long axis of voids with a long-axis length of $\geq 1 \mu\text{m}$. The voids were concentrated within $50 \mu\text{m}$ from the pierced edge surface. The void density was therefore defined as the void number density per unit edge surface length (number/mm). The void number density was measured in the area within $50 \mu\text{m}$ from the edge surface across the fractured surface and the sheared surface. The long-axis length of voids was also measured. However, the voids around and at the tips of specifically large cracks were excluded from the measurement. The standard errors of visually measured void number density were calculated and indicated as error bars.

In 3), the samples before and after hole expansion and the samples prepared by stopping hole expansion before the hole-expansion limit was reached were subjected to microscope observation. First, the surface texture of the pierced edge surface was evaluated using a microscope. Also, the crack shape was evaluated semiquantitatively on the basis of the shape profile of cracks obtained from observation vertically above the pierced edge surface using a laser microscope. We say "semiquantitatively" because the depth of cracks was underestimated by the measurement method adopted in this study for the cracks propagating from the sheet surface inward in an oblique direction. The observed areas were cut from the test specimens and subjected to the observation.

In this article, the amount of hole expansion deformation in the test specimens after stopping the hole expansion at a hole-expansion ratio λ' and in the test specimens during deformation was called the hole-expansion ratio λ' to prevent confusion with the hole-expansion limit λ that is generally used to refer to the fracture limit.

3. Experimental results

3.1 Observation of macrocrack propagation in hole-expansion tests

Figure 4 shows the images of samples during the propagation of the initial cracks, when the cracks reached the center of the sheet thickness, and when the cracks penetrated the sheet thickness

during JIS Z 2256 hole-expansion tests, which were clipped from the video of hole-expansion tests.

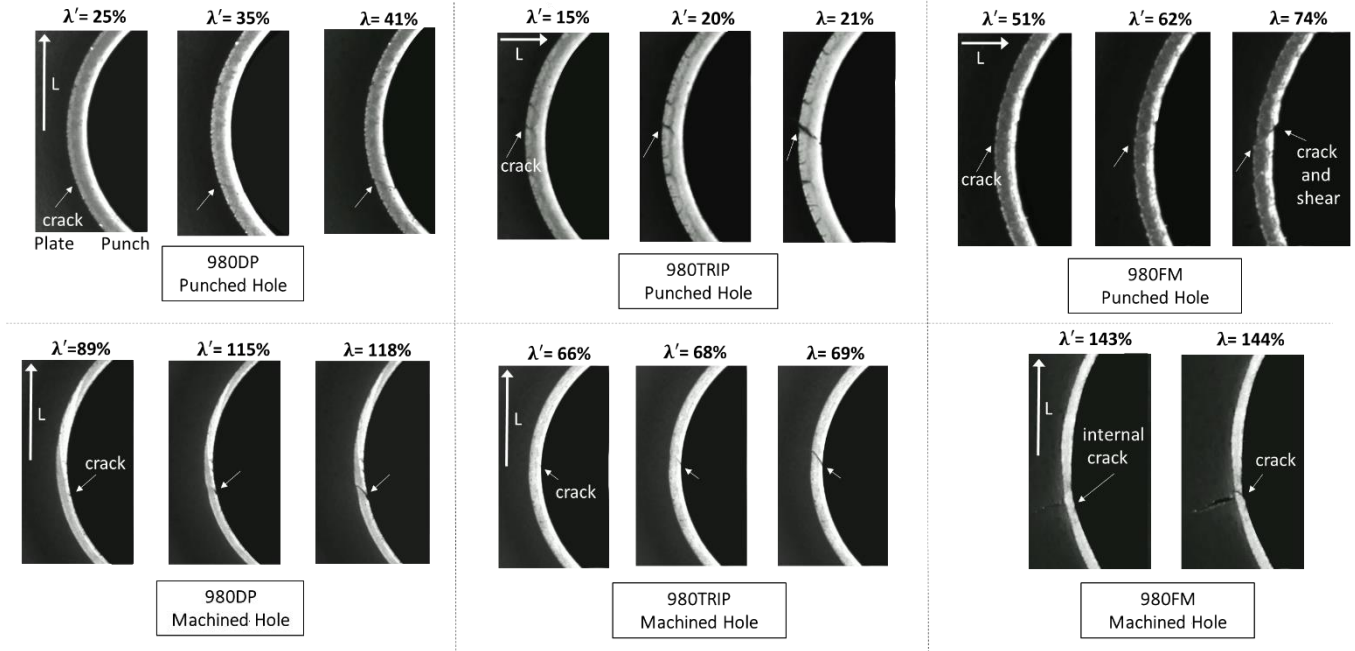


Fig. 4 Subsequent images of the crack propagation on the pierced edge of 980 DP and TRIP, FM steels obtained by JIS Z 2256 hole-expansion tests

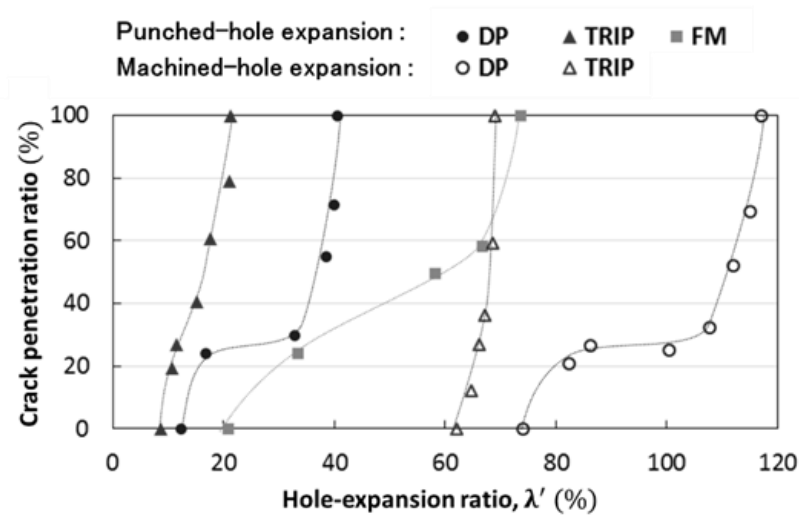


Fig. 5 Crack propagation ratio related to hole-expansion ratio observed macroscopically

Figure 5 shows the hole-expansion ratio λ' under the applied load measured from the video images and its relationship with the penetration ratio, i.e., the ratio of penetration to the sheet thickness, of the cracks that eventually penetrated the sheet thickness. The penetration ratio plotted at 0% indicates the time when an initial crack was observed in the video, and the penetration ratio plotted at 100% indicates the time when stretch-flange cracking was identified on the basis of the penetration of a crack. The machined hole of 980FM is not shown in the figure because the crack did not originate from the edge surface.

Initial cracks were formed in the punched holes of 980TRIP, 980DP, and 980FM, in this order, in the initial stage of hole expansion ($\lambda' = 10\text{--}20\%$). Initial cracks were formed in the machined holes of 980TRIP and 980DP, in this order, in the later stage of hole expansion ($\lambda' = 60\text{--}80\%$). However, no crack was formed in the machined hole of 980FM by hole expansion. The sample of the machined hole of 980FM fractured owing to the internal cracking that occurred inside the edge surface because of the local reduction of sheet thickness.

Obvious cracks propagated at a lower hole-expansion ratio λ' in the punched holes of 980TRIP, 980DP, and 980FM, in this order. The hole-expansion ratio λ' representing the amount of deformation from

the point of initial crack formation to the point of penetration was approximately 10, 25, and 50% for 980TRIP, 980DP, and 980FM, respectively. The initial cracks propagated rapidly in 980TRIP immediately after formation. The initial cracks once stagnated in 980DP at the penetration ratio of ~25% and then propagated rapidly at the penetration ratio of ~35%. The initial cracks propagated slowly in 980FM up to the penetration ratio of ~60% and then propagated rapidly. A similar crack propagation behavior was observed in the machined holes.

3.2 Observation of microstructure inside edge surface after punching and hole expansion

Figure 6 shows the cross-sectional SEM images and micrographs of the pierced edge surface after punching. The proportion of sheared surface and the maximum peak height of the roughness of the fractured surface, R_p (measured by a laser microscope), are also indicated in the figure. The proportion of sheared surface after punching was higher, in descending order, in 980FM (41%), 980DP (21%), and 980TRIP (13%), which agreed with the excellence of the hole-expansion limit λ . The maximum peak height R_p representing the surface roughness of the fractured surface was 5.5, 10, and 17 μm in 980DP, 980TRIP, and 980FM, respectively. No correlation was found between the maximum peak height and the hole-expansion limit λ in the types of steel used in this study.

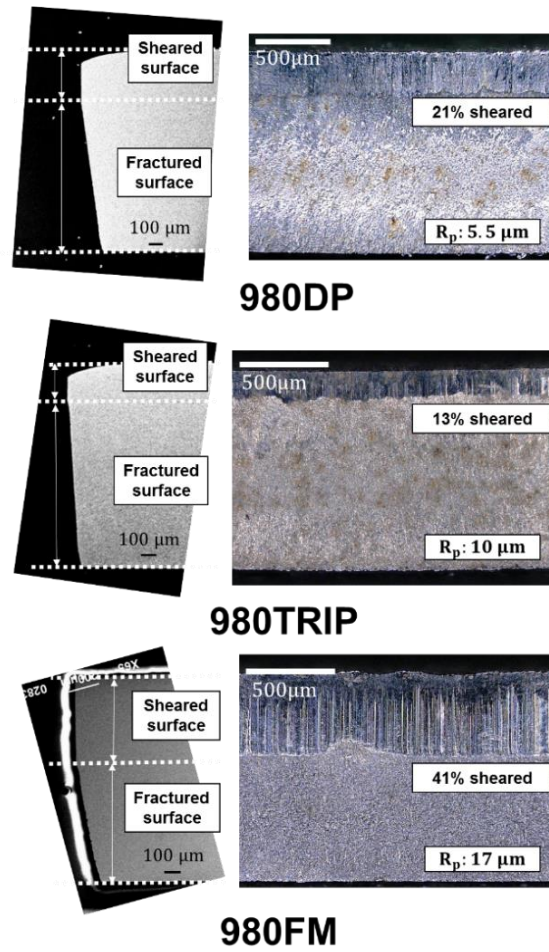


Fig. 6 Cross sectional and surface micrographs of punched holes

Figure 7 shows the cross-sectional SEM images of the pierced edge surface after hole expansion and the SEM images of crack tips after etching. Locally propagating cracks were observed on the pierced edge surface of the samples after hole expansion. Marked void formation and coalescence were observed only around the crack tips. No clear void formation and coalescence were observed inside the edge surface except at the area near the edge surface and the periphery of cracks in any type of steel. The same results were observed in the mirror-polished surface.

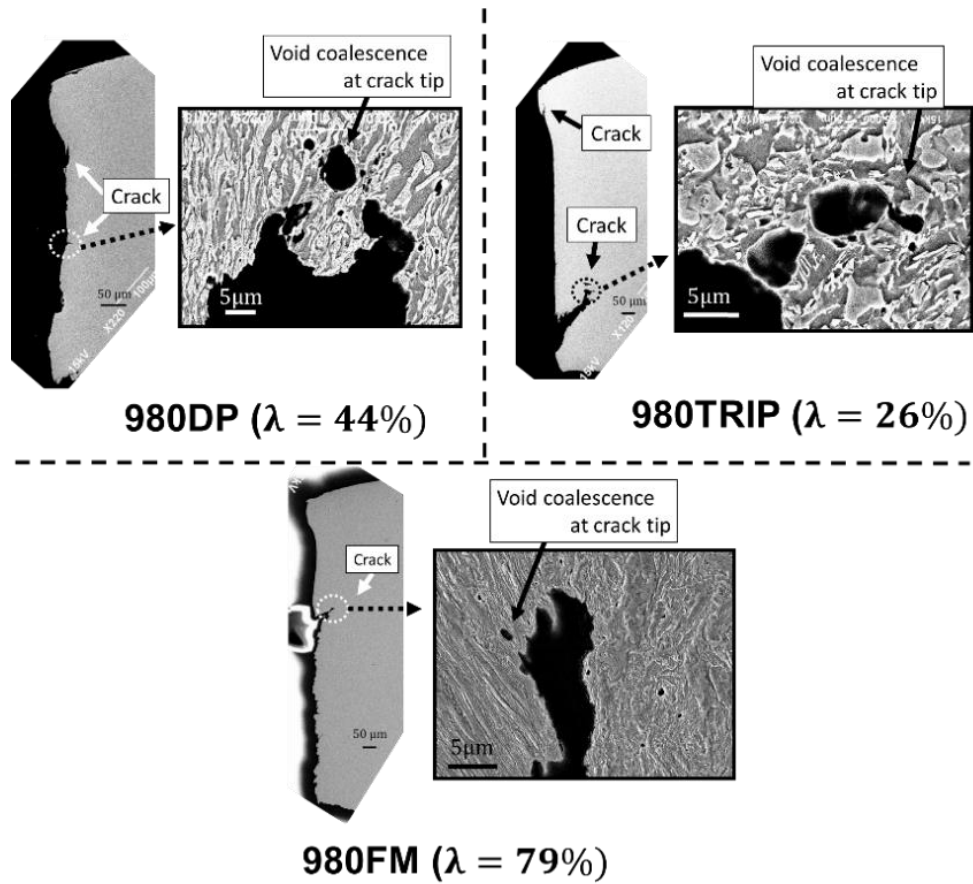


Fig. 7 Cross-sectional SEM images of expanded holes and their crack tip areas

Figure 8 shows the typical SEM images of the etched fractured surface without cracks after punching and those after hole expansion. The metal flow and the surface layer of the fractured surface after punching and the surface layer of the fractured surface after hole expansion are shown in the figure. The bright areas are martensite and retained austenite regions that were not easily etched, whereas the dark areas are easily etched ferrite and bainite regions.

In the metal flow, the crystal grains were elongated in the punching direction in the area within $\sim 50\ \mu\text{m}$ from the fractured surface. The work-hardened layer was assumed to exist in this area.

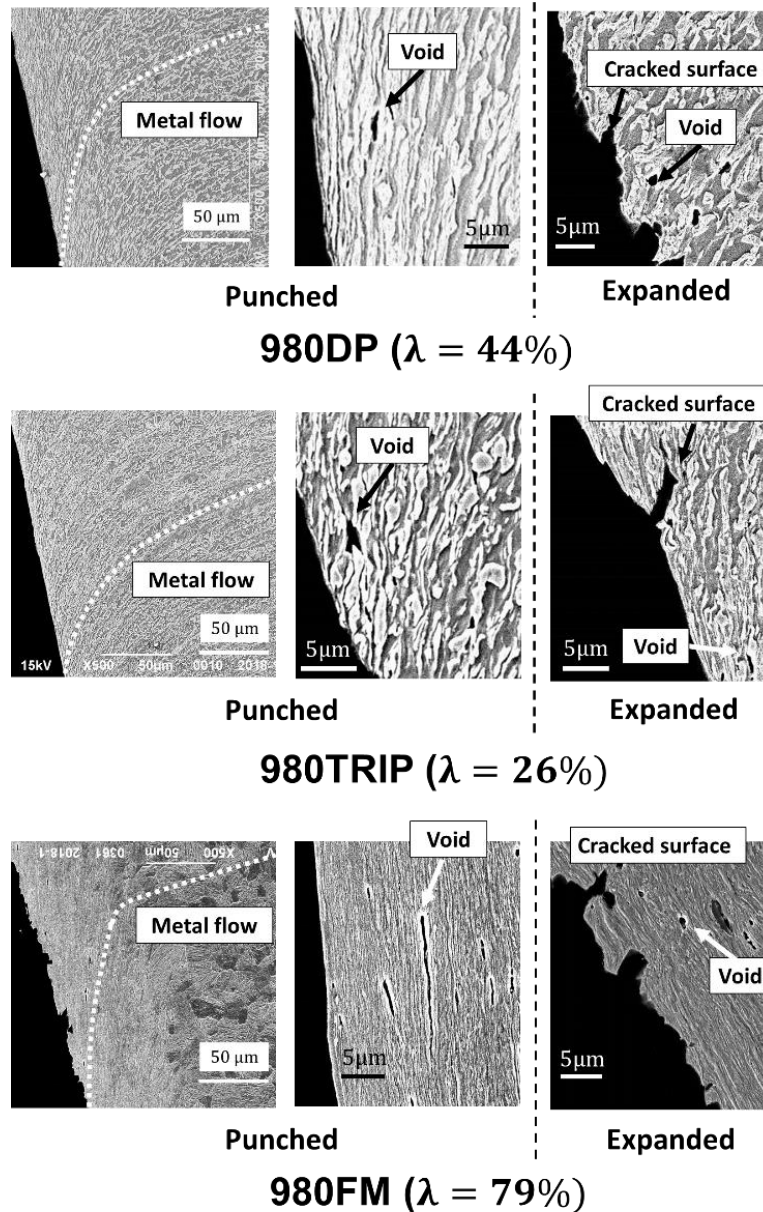


Fig. 8 Cross-sectional SEM images of punched and expanded holes in the fractured surface areas

(Bright: martensite or austenite, Dark: ferrite or bainite)

In the samples after punching, voids were found in the work-hardened layer in the area within $\sim 50\text{ }\mu\text{m}$ from the edge surface. The voids were formed in the phase interface between ferrite and martensite in 980DP and in the interface between hard phases such as martensite and retained austenite indicated by bright areas in 980TRIP. Longitudinal voids were formed along with the metal flow in 980FM. The location of void formation agreed with that in previous reports [12,13,17,29].

In the samples after hole expansion, some voids formed by punching cleaved the surface and were observed as microcracks. The apparent number of voids decreased because the formation of new voids was minimal. Figure 9 shows the change in the void number density measured before and after hole expansion on the mirror-polished surface excluding the periphery of particularly large cracks. The void number density significantly decreased after hole expansion. No significant increase in the long-axis length of voids was observed, although this is not indicated in the figure.

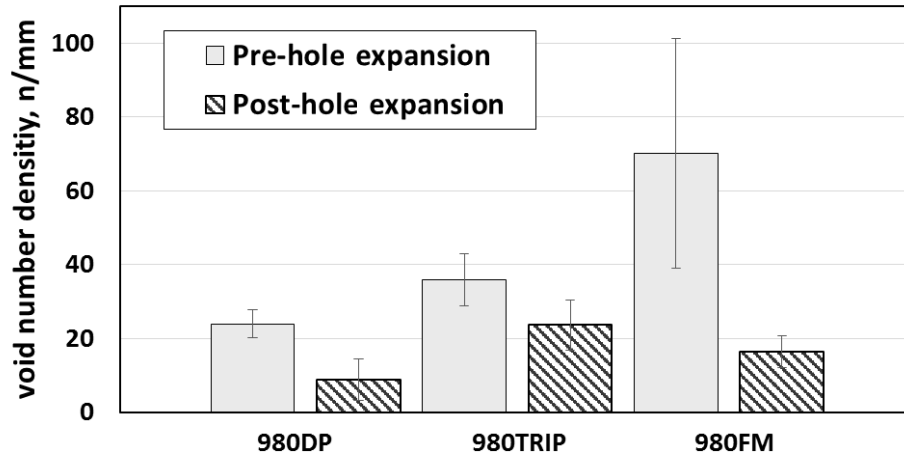


Fig. 9 Void number density changes in pre- and post- hole-expansion test specimens

3.3 Observation of edge surface microgeometry after punching and hole expansion

Figure 10 shows the overall micrographs observed from vertically above the pierced edge surface of machined holes before and after the hole-expansion tests. Roughness with a height of $\sim 5 \mu\text{m}$ caused by reaming was observed in all types of steel before hole expansion. A single deep crack was observed, but no other changes in the surface shape were observed in 980DP and 980TRIP after hole expansion. On the other hand, the sample of 980FM fractured as a result of the internal cracking around a crack because of the local reduction of sheet thickness, as described in 3.1.

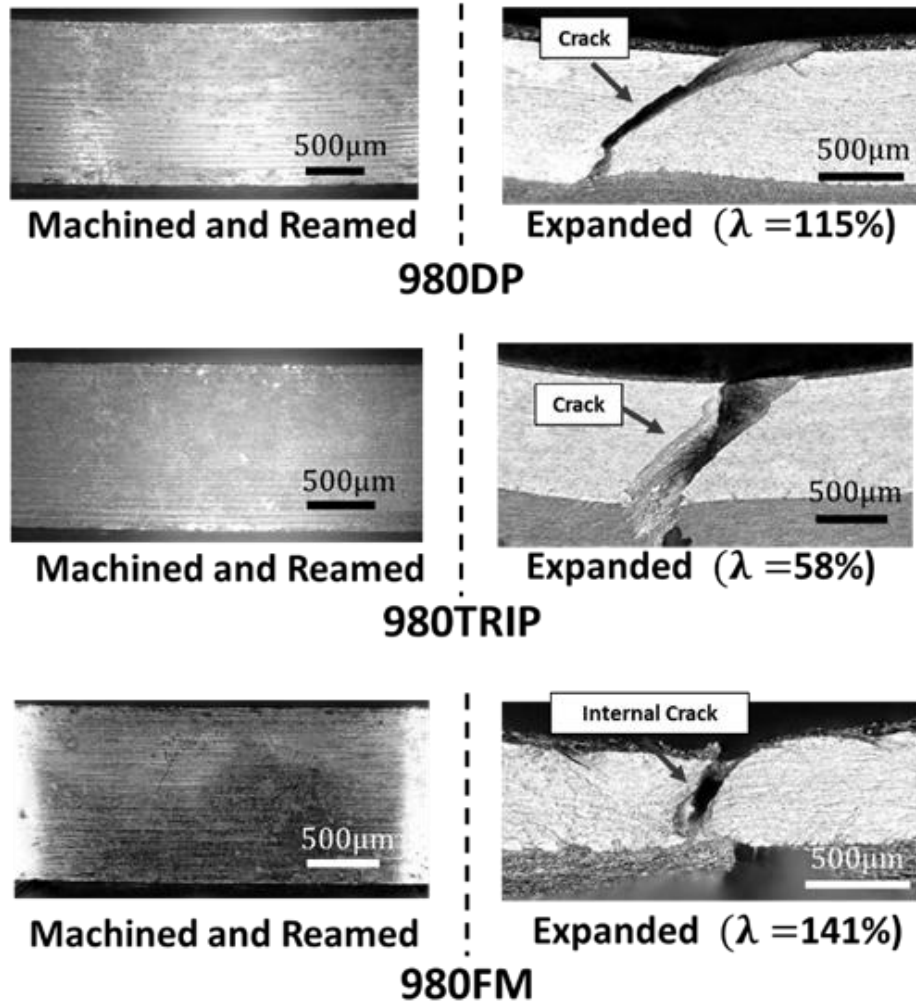


Fig. 10 Surface micrographs of expanded specimens with machined and reamed holes

Figures 11-13 show the micrographs of punched holes of 980DP, 980TRIP, and 980FM after hole expansion and those obtained by stopping hole expansion at a hole-expansion ratio λ' . These figures show the overall micrographs of each type of steel viewed from vertically above and the crack shape (opening width and depth) measured with a laser microscope at the same hole-expansion ratio λ' next to each micrograph. Note that the crack shape was evaluated

using the measured values of the deepest point of cracks. A sample was prepared for each hole-expansion ratio λ' . The area around the crack that propagated the most was cut from the sample and subjected to the observation.

The fracture behavior in each type of steel associated with hole expansion is explained below.

In Fig. 11, a shallow initial crack was formed on the burr side of the fractured surface of 980DP in the initial stage of hole expansion ($\lambda' = 14\%$). The initial crack propagated to the penetration ratio of $\sim 25\%$ and stagnated in the middle stage of hole expansion ($\lambda' = 25\%$), increasing in width and depth but being stunted in length. This result corresponded to the crack stagnation at the same penetration ratio recorded in the video of hole expansion and shown in Fig. 5. At the same time, in the middle stage of hole expansion ($\lambda' = 25\%$), a black streak of a shear-like crack (hereinafter called the "shear crack") was formed from the pierced edge surface at around the center of the sheet thickness at an angle of about 45° relative to the direction of uniaxial deformation of the sheet. The initial crack was further stunted in length and stagnated when stretch-flange cracking was identified ($\lambda = 45\%$). On the other hand, the shear crack grew markedly. The shear crack coalesced with an initial crack, propagated in the sheet thickness direction, and penetrated and

cleaved the sheared surface, resulting in the identification of stretch-flange cracking.

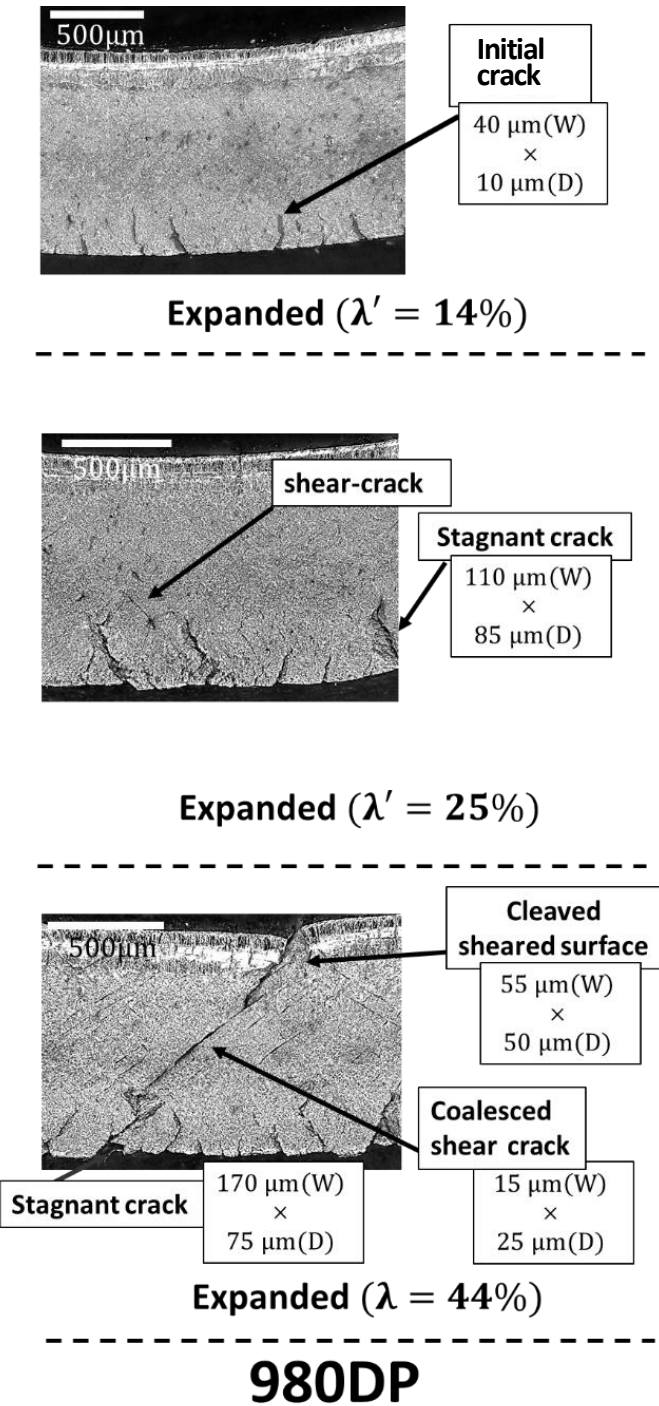


Fig. 11 Surface micrographs of expanded 980DP specimens with punched hole (W: crack width, D: crack depth)

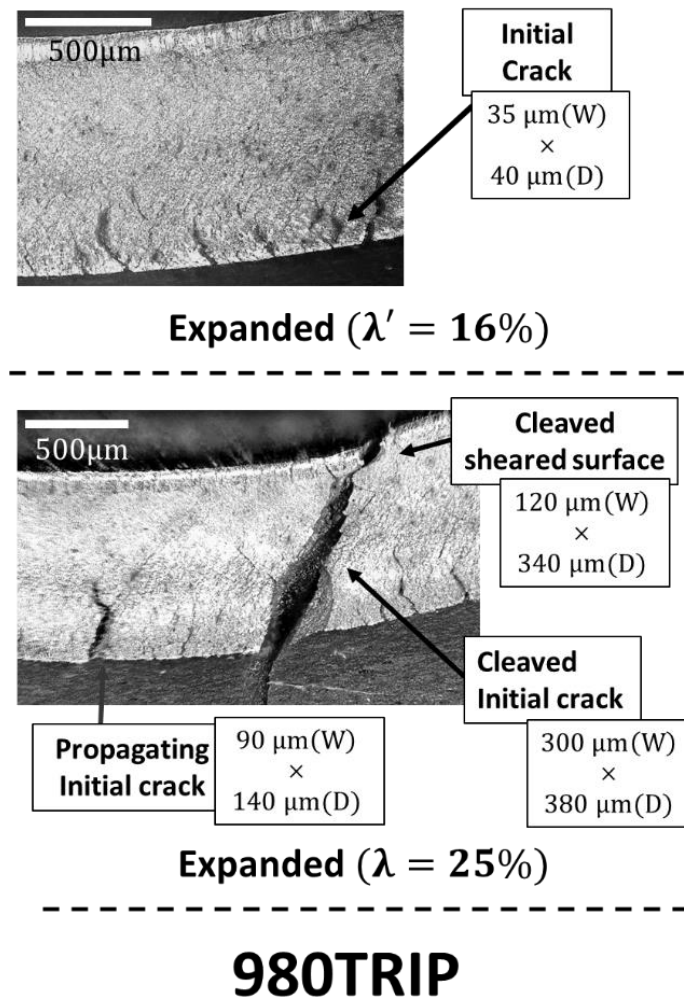


Fig. 12 Surface micrographs of expanded 980TRIP specimens with punched hole (W: crack width, D: crack depth)

In Fig. 12, an initial crack was formed on the fractured surface of 980TRIP in the initial stage of hole expansion ($\lambda' = 16\%$). This initial crack was deeper than that in 980DP. A deep, sharp, and propagating initial crack was observed at the time when stretch-flange cracking was identified ($\lambda = 25\%$). A very deep crack penetrated the sheet thickness and cleaved the sheared surface completely with a large opening, resulting in the identification

of stretch-flange cracking. Different from 980DP, shear cracks did not propagate considerably. The initial crack propagated and penetrated the sheet thickness on its own.

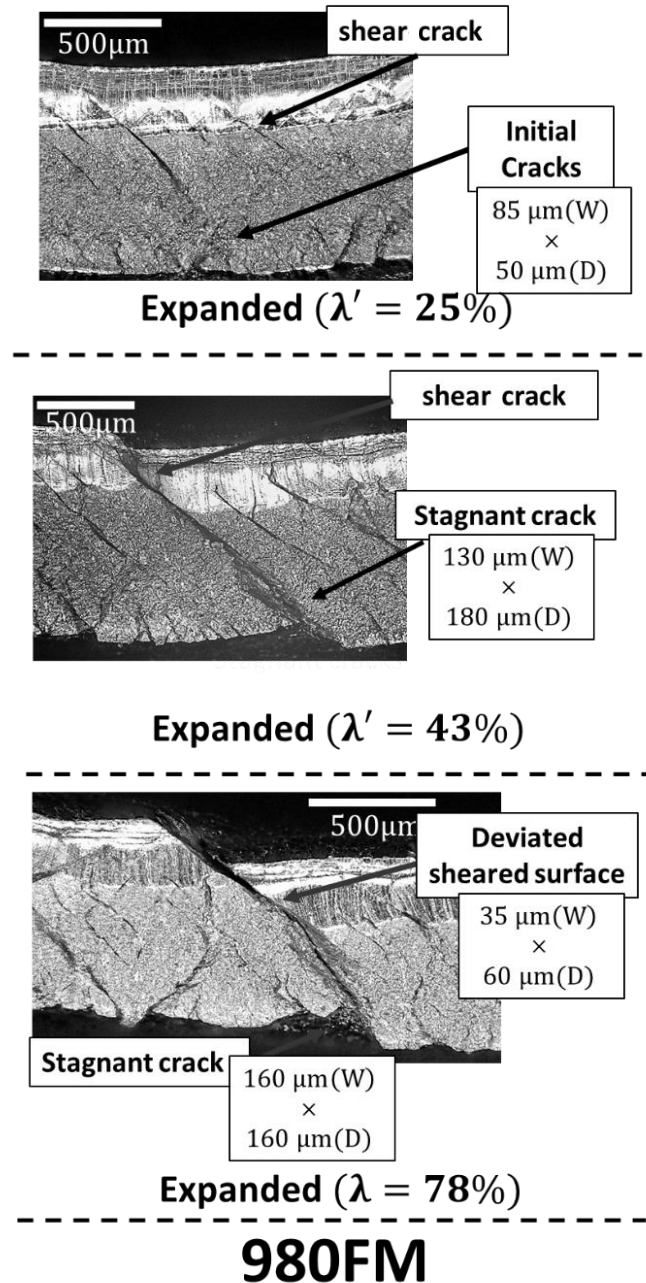


Fig. 13 Surface micrographs of expanded 980FM

specimens with punched hole (W: crack width, D: crack depth)

In Fig. 13, in addition to initial cracks, a prominent shear crack was formed in 980FM in the initial stage of hole expansion ($\lambda' = 25\%$). The shear crack coalesced with an initial crack in the middle stage of hole expansion ($\lambda' = 43\%$) and propagated in the sheet thickness direction to reach the sheared surface. However, different from 980DP, the shear crack did not penetrate the sheet thickness or cleave the sheared surface. The sheared surface remained continuous. The sheared surface was sheared and divided at the macro level along with a shear crack when $\lambda = 78\%$. At the same time, the shear crack penetrated the sheet thickness, resulting in the identification of stretch-flange cracking.

4. Discussion

4.1 Macrocrack propagation behavior in different types of steel

The fracture mechanism related to the hole-expansion limit of punched holes in the UHSSs made of different types of steel is discussed below referring to the experimental results. The expansion of $\Phi 10$ mm holes using a conical punch with an apex angle of 60° (JIS Z 2256), which was carried out in this study, is one of the forming conditions for high-strain-gradient areas³¹⁾, representing the cases of stretch-flange cracking from the edge surface under uniform deformation.

The formation and propagation behavior of cracks differed depending on the type of steel and the conditions of punched holes, as shown

in Fig. 4. The phenomenon of stretch-flange cracking depending on the type of steel and edge surface conditions can be investigated by analyzing the crack behavior in detail.

Figure 5 shows that the initial cracks were formed in the punched holes of 980TRIP, 980DP, and 980FM, in this order, in the initial stage of hole expansion ($\lambda' = 10\text{--}20\%$). However, the difference in the hole-expansion ratio λ' was small at the time of crack formation. On the other hand, there was a large difference in the earliness of crack propagation relative to the hole-expansion ratio λ' .

The above results indicated that the hole-expansion limit λ of punched holes was most significantly affected by the earliness of crack propagation. The crack propagation in 980TRIP was extremely rapid. Different from the cracks in 980DP and 980FM, the cracks did not stagnate in 980TRIP. This may be the reason for the markedly low hole-expansion limit λ of 980TRIP. The formation of initial cracks was very slow in machined holes. These results suggested that the work-hardened layer generated by punching was closely related to the formation of initial cracks.

4.2 Microfracture behavior inside edge surface of different types of steel

On the basis of the discussion in 4.1, the crack formation and propagation were examined from more microscale perspectives.

The two typical mechanisms of formation and propagation of ductility cracks in steel materials are as follows.

- I. Void formation and coalescence throughout plastic-worked area.
- II. Local void formation and coalescence at crack tips.

Mechanism I has been observed in uniaxial tensile tests and tensile stretch-flangeability tests^{12),13),32)}, whereas mechanism II has been observed in the hole-expansion tests of DP and FM20³⁰⁾ and the fracture toughness tests of TRIP³³⁾.

In this study, the crack propagation behavior and the void formation behavior in different types of steel associated with hole expansion were investigated by SEM observation inside the punched edge surface before and after hole expansion.

No clear void formation and coalescence were observed inside the edge surface even after hole expansion, as shown in Fig. 7. However, the local propagation of cracks from the edge surface was observed. Voids were formed and coalesced at the crack tips, leading to the ductile crack propagation. These results suggested that the stretch-flange cracking in high-strain-gradient areas of UHSSs

with a tensile strength of 980 MPa grade was caused by the local fracture phenomenon at crack tips (mechanism II).

Some voids in the work-hardened layer generated by punching cleaved the edge surface and formed microcracks, as shown in Fig. 8. The voids in the work-hardened layer were consumed as the source of microcracks as the hole expansion progressed. The void number density near the edge surface decreased after the edge surface fractured owing to hole expansion, as shown in Fig. 9. This result suggested that void formation throughout the plastic-worked area (mechanism I) was not considerable.

4.3 Behavior of work-hardened layer in punched holes of different types of steel

On the basis of the discussion in 4.1 and 4.2, the behavior of the work-hardened layer associated with hole expansion was examined by observing the pierced edge surface in order to understand the microcrack propagation behavior in the sheet thickness direction of different types of steel.

Regarding the machined holes that were less affected by the work-hardened layer, Fig. 10 shows that no changes in the surface texture other than cracks were observed in 980DP and 980TRIP before the edge surface fractured owing to hole expansion. An increase in surface roughness around a crack was observed in 980FM; however,

this was caused by the local reduction of sheet thickness owing to plastic instability.

Regarding the punched holes, Figs. 11-13 show that the initial cracks were formed in the initial stage of hole expansion ($\lambda' = 10-20\%$), and the shear cracks grew on the edge surface as the hole expansion progressed. Upon comparing these results with those in the machined holes shown in Fig. 10, the formation of initial cracks and shear cracks in the punched holes was considered to be caused by the presence of a work-hardened layer.

As apparent in 980FM shown in Fig. 13, the edge surface was deviated in a planar manner in an oblique direction owing to the shear crack. There was no level difference between the two sides of the shear crack. The shear crack sheared the outermost layer of the edge surface obliquely relative to the uniaxial tensile direction while contributing to the macrodeformation of the work-hardened layer.

The formation of shear cracks was explained as follows. The retained ductility in the work-hardened layer of the edge surface was much lower than that in the unhardened inner microstructure. The work-hardened layer therefore could not follow the uniaxial tensile deformation of the inner microstructure during the hole expansion. The work-hardened layer immediately exhibited plastic instability as the hole-expansion deformation progressed, which

resulted in local shear deformation. Such shear deformation led to the formation of narrow and shallow shear cracks while cleaving the voids in the work-hardened layer.

The formation of initial cracks is explained as follows. The first possible cause was the cleavage of initial voids mentioned in 4.2. Also, the orientation of initial cracks was almost the same as that of shear cracks. This result suggested that the shear cracks formed on the burr side of the fractured surface in the initial stage of hole expansion were cleaved and became initial cracks.

4.4 Microcrack propagation behavior in different types of steel

The initial cracks and shear cracks mentioned in 4.3 were commonly observed in the punched holes of 980DP, 980TRIP, and 980FM. However, there were considerable differences in the behavior of cracks propagating to fracture depending on the type of steel. The effects of different fracture morphologies and material properties on the hole-expansion limit are examined below by comparing the behaviors of initial cracks and shear cracks in different types of steel.

Figure 14 shows the proposed flowchart of the fracture behavior in the punched holes of 980DP, 980TRIP, and 980FM shown in Figs. 11-13. The hole-expansion fracture mechanism and its differences depending on the type of steel are described below.

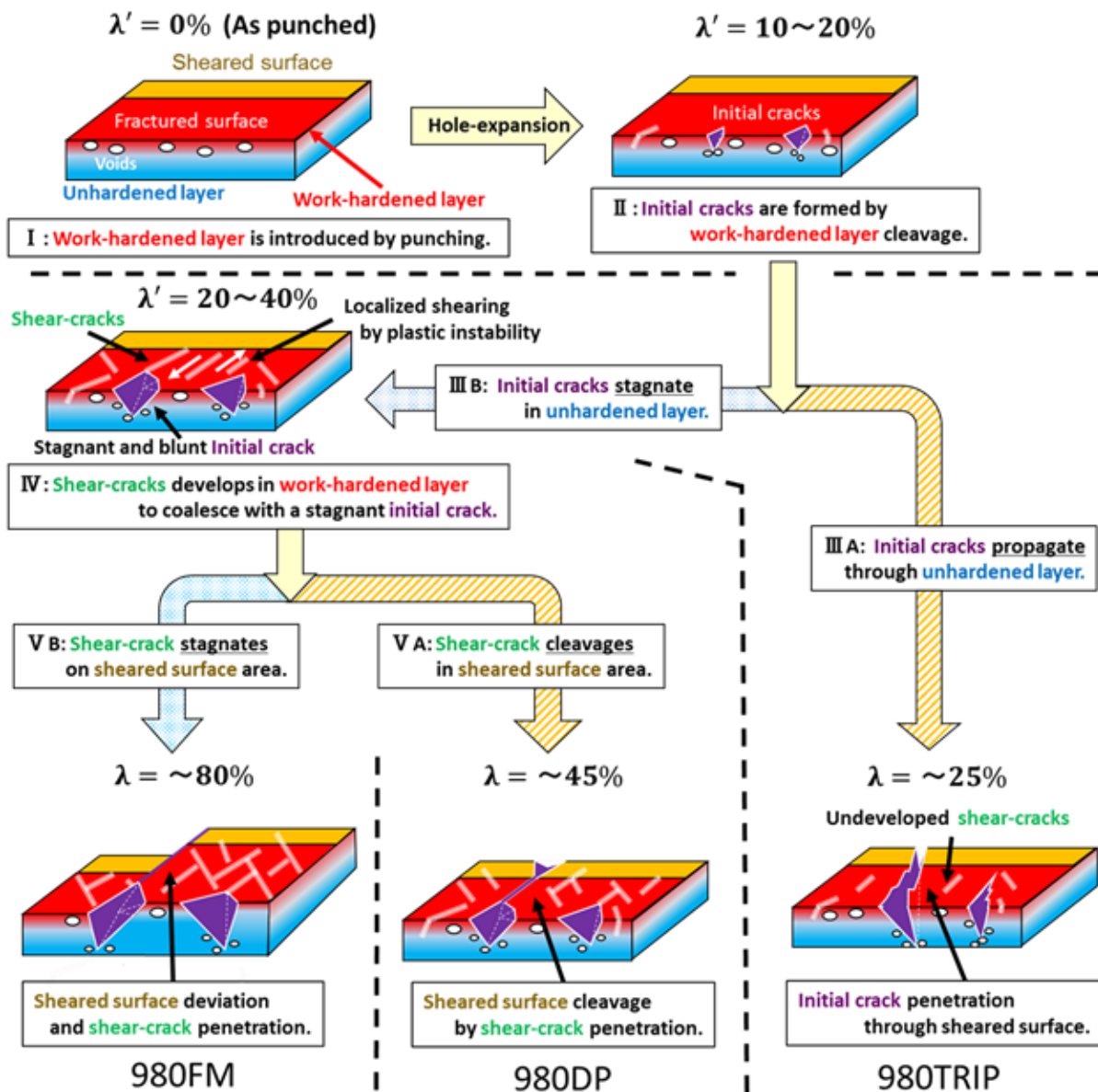


Fig.14 Suggested flowchart of stretched-flange fracture mechanism on punched surfaces according to different types of steels

The pierced edge surface prepared by punching ($\lambda' = 0\%$) contained the work-hardened layer consisting of the sheared surface and the fractured surface and the unhardened microstructure inside the work-hardened layer. When the punched holes were expanded, initial cracks were formed by the cleavage of the fractured surface in the work-hardened layer in the initial stage of hole expansion ($\lambda' = 10\text{--}20\%$). Thus far, the crack behavior appears to be common to all types of steel.

In the subsequent stages of hole expansion ($\lambda' \geq 20\%$), the initial cracks rapidly propagated and penetrated the sheet thickness in 980TRIP, whereas the initial cracks stagnated in 980DP and 980FM. These results indicated that the differences in the fracture behavior in the middle stage of hole expansion ($\lambda' = 20\text{--}40\%$) were attributed to the differences in the propagation behavior of initial cracks.

From the metal flow shown in Fig. 8, the thickness of the work-hardened layer was assumed to be $\sim 50\text{ }\mu\text{m}$. Therefore, the tips of initial cracks in each type of steel were assumed to reach the inner microstructure unaffected by punching. The propagating initial cracks and the penetrating cracks observed in 980TRIP were significantly deeper than those observed in 980DP (Fig. 11) and 980FM (Fig. 13). Those cracks penetrated the sheet thickness without stagnation. On the other hand, the initial cracks in 980DP

and 980FM stagnated simultaneously in both the depth direction and the sheet thickness direction in the inner microstructure, which was why they did not penetrate the sheet thickness. These results suggested that the first branch point of stretch-flange fracture was whether the propagation of initial cracks was stopped or not in the microstructure inside the work-hardened layer. The hole-expansion limit λ of 980TRIP was very low because the crack easily propagated to the inner microstructure. In general, retained austenite easily undergoes stress-induced transformation to martensite in the plastically deformed area at the crack tips in TRIP steels. It has been reported that this stress-induced martensite acts as the propagation path of cracks and significantly decreases the resistance of TRIP steels to crack propagation³³).

The initial cracks that stagnated in 980DP and 980FM grew through coalescence with the shear cracks in the middle stage of hole expansion ($\lambda' = 20-40\%$), propagating in the sheet thickness direction. The shear cracks reached the sheared surface in both 980DP and 980FM when stretch-flange cracking was identified in 980DP ($\lambda' \approx 45\%$). At this time, the shear cracks cleaved the sheared surface in 980DP but the shear cracks stagnated on the sheared surface and did not penetrate the sheet thickness in 980FM. The edge surface was significantly shear-deformed along the shear cracks when stretch-flange cracking was identified in 980FM ($\lambda' =$

78%). The sheared surface was divided and, at the same time, the shear cracks penetrated the sheet thickness.

These results suggested that the differences in the fracture behavior in the late stage of hole expansion ($\lambda' = 40\text{--}80\%$) was attributed to the differences in the propagation behavior of shear cracks. The stretch-flange cracking was identified earlier in 980DP because shear cracks easily propagated and penetrated the sheared surface. On the other hand, crack penetration was not identified until the edge surface was sheared at the macroscale level in 980FM because the shear cracks stagnated on the sheared surface. Generally, voids rarely formed between different phases of adequately tempered FM steels because such steels have a fine, homogeneous, and soft microstructure^{26)–28)}. This was assumed to be the reason why 980FM showed high resistance to crack propagation.

The above results showed that the difference in the hole-expansion limit λ , which was higher, in ascending order, in 980TRIP, 980DP, and 980FM, can be attributed to the difference in the resistance of those steels to the propagation of initial cracks and shear cracks that are generated from the work-hardened layer. Furthermore, the resistance to crack propagation was a material factor that affected the stretch-flangeability. The stretch-flangeability was assumed to be higher in materials with higher resistance to crack propagation.

One of the quantitative indicators representing the resistance of materials to crack propagation and cleavage is the fracture toughness against ductile crack propagation. A strong correlation between the hole-expansion limit λ and the fracture toughness in high-strength steels has been reported¹⁹⁾⁻²²⁾. Those reports are consistent with the mechanism of stretch-flange fracture suggested by the results of this study.

5. Conclusion

With the aim of finding the material factor that affects the stretch-flangeability of UHSSs, we investigated the fracture mechanism related to stretch-flangeability by performing hole-expansion tests on the high-strain-gradient areas using DP, TRIP, and FM steels with a tensile strength of 980 MPa grade. The following findings were obtained.

- I. Macroscale fracture behavior of different types of steel and its effects on hole-expansion limit
 - (1) Initial cracks were formed in the punched holes of 980TRIP, 980DP, and 980FM, in this order, in the initial stage of hole-expansion deformation ($\lambda' = 10-20\%$). However, the difference in the hole-expansion ratio λ' at the time of crack formation was small, and its effects on the hole-expansion limit λ were insignificant.

- (2) The propagation of initial cracks was earlier relative to the hole-expansion ratio λ' , in descending order, in 980TRIP, 980DP, and 980FM. The difference in the earliness of crack propagation was considerable and most strongly affected the hole-expansion limit λ .

II. Behavior of voids and work-hardened layer in fractures

- (1) After hole-expansion fracture, voids were formed and coalesced locally only at the tips of cracks propagating from the edge surface in all types of steel. No clear void formation or coalescence was observed throughout the plastic-worked area other than at the crack tips. These results suggested that the stretch-flange cracking in this study was a phenomenon of local crack propagation.
- (2) In the work-hardened layer generated by punching, initial cracks were formed on the fractured surface and shear cracks were formed obliquely relative to the tensile direction in all types of steel owing to hole-expansion deformation. The reasons for the crack formation were the localization of strain owing to the plastic instability of the work-hardened layer and the cleavage of voids formed by punching in the work-hardened layer.

III. Differences in crack propagation behavior depending on type of steel and material factors affecting stretch-flangeability

- (1) The fracture behavior in the expansion of punched holes differed depending on the type of steel. The results below are listed in the order of the hole-expansion limit λ from the lowest to highest, or in other words, the earliness of crack propagation relative to the hole-expansion ratio λ' from the earliest to the latest.

980TRIP: Crack penetration due to propagation of initial cracks alone.

980DP Coalescence of initial cracks with shear cracks and cleavage of the sheared surface by shear cracks.

980FM: Division of sheared surface and penetration of shear cracks through the sheet thickness owing to shear of the edge surface along with shear cracks at the macroscale level.

- (2) The differences in the crack propagation behavior on the edge surface of punched holes was attributed to the propagation and cleavage behavior of initial cracks and shear cracks formed in the work-hardened layer. The results suggested that the microstructural resistance to crack propagation was a material factor affecting the stretch-flangeability.

6. Declarations

a.Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

b.Conflicts of interest/Competing interests

The authors have no relevant financial or non-financial interests to disclose.

c.Authors' contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Yuichi MATSUKI]. The first draft of the manuscript was written by [Yuichi MATSUKI] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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