

# Hole expansion behavior of hot-rolled steel related to punching morphology considering banded microstructure

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**Abstract.** The hole expansion behavior serves as a key metric for assessing the formability of automotive structural components containing holes. With the growing emphasis on decarbonization in automotive manufacturing, hot-rolled steels have gained attention as promising substitutes for cold-rolled counterparts. Owing to their thermomechanical processing characteristics, hot-rolled steels frequently exhibit banded microstructures oriented along the rolling direction; however, the effect of these banded structures on hole expansion behavior remains insufficiently understood. In the present work, two hot-rolled steels with distinct banded morphologies were investigated under punching conditions in accordance with ISO 16630. The study focused on the evolution of microstructural features within the shear-affected zone (SAZ) and at the hole-edge surface before and after hole expansion. The findings indicate that the banded arrangement facilitates circumferential crack propagation along the hole edge, thereby improving hole expansion performance. This advantageous effect is particularly evident when the fracture zone constitutes a large fraction of the hole-edge surface, promoting stress relief through the generation of cross cracks. In contrast, when the fracture zone is limited, fracture initiation in the burr zone at the hole periphery leads to visible hole expansion cracks, contributing to the safe identification of failure during service. Additionally, the matrix hardness and strength were found to play a decisive role in governing hole expansion behavior, with a positive correlation established between edge hardening induced by punching and the hole expansion ratio.

**Keywords:** Hole expansion behavior / shear affected zone / advanced high strength steel / banded structure

## 1 Introduction

Steel has long been regarded as the primary material for automotive applications, owing to its economic efficiency, design flexibility, and sustainability throughout the entire product lifecycle. In the context of global decarbonization strategies, the automotive industry is increasingly required to enhance fuel efficiency and minimize carbon emissions [1]. Lightweighting has emerged as a pivotal approach to reducing fuel consumption [2], thereby driving the advancement of advanced high-strength steels (AHSS). With the progression toward high-precision and integrated manufacturing in automotive engineering, structural components have become increasingly geometrically complex, particularly those containing punched holes, imposing stringent requirements on the performance optimization of AHSS. During forming, plastic deformation tends to localize at geometrically constrained regions, especially in the vicinity of hole edges. Fracture in such

regions often occurs abruptly, without observable thinning or necking, which poses significant challenges to structural safety and service reliability [3]. The hole expansion ratio (HER), as defined by ISO 16630, is extensively utilized to characterize the formability of thin sheets with holes [4–6]. The standard testing procedure involves two sequential stages: initially, a hole of 10 mm diameter is punched into a 90 mm × 90 mm specimen using a suitable clearance relative to the sheet thickness; subsequently, the hole is expanded using a 60° conical punch. The test is terminated upon the detection of a through-thickness crack at the hole edge. Hole expansion property is quantified by calculating the relative increase in hole diameter, expressed as HER.

Aligned with the objectives of decarbonization and sustainable metallurgical practices, the substitution of cold-rolled annealed products—which entail prolonged, energy-intensive processing—with hot-rolled products represents a forward-looking strategy [7,8]. Given that hot-rolled steels are not tailored by isothermal annealing, their microstructures predominantly exhibit rolling-directional banding [9]. Such banded microstructural distributions induce heterogeneity in local mechanical properties,

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consequently affecting deformation mechanisms and formability, particularly in regions with localized features such as holes, where uncertainty is elevated [10]. This issue necessitates further rigorous investigation. Existing literature predominantly addresses the compositional aspects of microstructures, emphasizing the influence of multiple phases on localized forming characteristics. Notably, numerous studies employing the ISO 16630 standard have reported excellent hole expansion performance in multi-phase steels containing multiple microstructures, such as ferrite, bainite, and martensite [11,12]. A prevailing consensus attributes this enhancement to the mitigation of hardness disparities among phases, which reduces strain localization at phase interfaces and facilitates coordinated plastic deformation via dislocation pile-up accommodation at hetero interfaces (phase boundaries) [13,14]. Nevertheless, to the authors' knowledge, investigations into the effects of microstructural distribution on hole expansion remain sparse and yield contradictory conclusions.

Certain studies contend that continuous microstructural bands aligned with the rolling direction exacerbate void deformation and coalescence, detrimentally influencing formability; thus, a homogeneous microstructure distribution is posited as optimal for achieving excellent performance [15,16]. Preliminary findings from the authors corroborate that dispersing island-like structures through volumetric control of high-hardness martensite-austenite (MA) constituents promotes a more uniform local strain distribution during deformation [17]. Such uniformity suppresses microcrack initiation via void coalescence under low-strain conditions, thereby stabilizing hole expansion behaviour. Conversely, alternative perspectives highlight that banded microstructures redirect crack propagation pathways and constrain crack growth through the sheet thickness, thereby enhancing the HER [18]. Prior investigations on an 800 MPa-grade complex phase steel—featuring approximately 20  $\mu\text{m}$  wide martensite-austenite (MA) constituents bands continuously aligned along the rolling direction at the specimen's thickness center, fabricated through controlled slab segregation—demonstrated significant improvements in hole expansion under punching conditions. The primary hardening zone shifted from the burr to the thickness center, facilitating the formation of circumferential cracks around the hole during deformation and promoting stress relaxation. Concurrently, alterations in the stress state induced necking prior to fracture, which optimizes the fracture mode [19]. Collectively, these findings affirm that continuous banded microstructures foster interconnected voids and microcrack development during deformation. However, the implications of such microcrack formation on hole expansion behaviour are multifaceted and perspective-dependent. Given the substantial influence of microcracks on subsequent hole expansion behaviour and HER, contingent on microstructures and microstructural distribution, a thorough and systematic evaluation of the effects of banded microstructure on hole expansion behaviour is warranted.

In the present work, two types of dual-phase steels exhibiting banded microstructures were fabricated by manipulating the coiling temperature. Hole expansion tests

were performed in accordance with ISO 16630 to investigate their formability. Initially, microhardness measurements were employed to quantify the degree of hardening within the shear affected zone (SAZ) following punching, thereby elucidating the correlation between microstructural characteristics and punching-induced hardening. Subsequently, the morphological features of distinct zones along the hole edge surface were systematically characterized and analysed. Although the hole edge surface serves as a critical reference for fracture assessment, its study has been limited due to the complexity of specimen preparation. Consequently, prior research has predominantly concentrated on the SAZ, with minimal emphasis placed on the detailed features of the hole edge surface [11,20, 21]. The present study extends beyond conventional SAZ-focused analyses by conducting a comprehensive morphological examination of the inner surface of the hole edge. Through multi-plane observations, a three-dimensional framework is proposed to elucidate the structural characteristics of the punched hole edge. Interrupted hole expansion tests were then conducted to capture the microstructure evolution of the hole edge during deformation and subsequent failure. Based on these investigations, the relationship between fracture mechanisms and underlying microstructure was established, leading to a comprehensive understanding of the hole expansion behavior in hot-rolled steels containing banded microstructures. The relevant conclusions lay the foundation for the relationship of AHSS banded microstructure on hole expansion behavior, which is helpful to further develop hot-rolled high hole expansion steel with short process prospects, such as thin slab continuous casting and rolling.

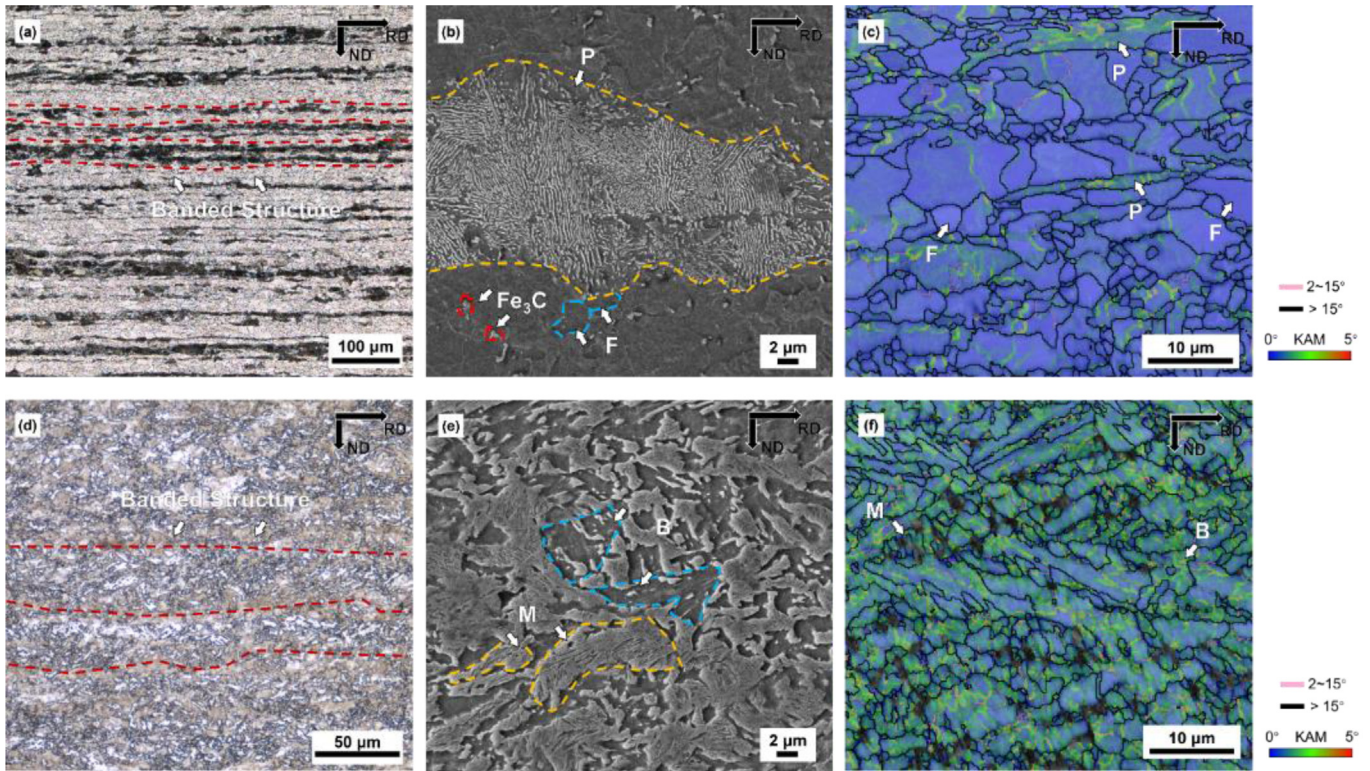
## 2 Material and methods

### 2.1 Materials preparation

The experimental steel was smelted in a vacuum induction melting furnace (VIM, ZGJ0.05-100-25) with the nominal chemical composition (wt.%) of 0.15C-1.4Si-1.8Mn-0.4Cr-0.18Mo-Fe. The molten metal was cast into a 50 kg ingot, subsequently forged into a bulk material with a thickness of 10 cm. To ensure chemical and microstructural homogeneity, the bulk was homogenized at 1200 °C for 1.5 h prior to hot rolling. The material was then hot rolled to a final thickness of approximately 2 mm through five passes using a single-stand four-high reversing mill.

Thermal expansion tests were carried out using a dilatometer (DIL 805A, BAEHR) to determine the phase transformation temperatures. Cylindrical specimens with a diameter of 4 mm and a height of 10 mm were heated to 1100 °C at a rate of 0.5 °C/s, held at that temperature for 5 min, and then cooled to room temperature at a rate of 20 °C/s. Based on the thermal expansion curve, the austenite transformation temperature  $A_{c3}$  was identified as approximately 920 °C.

To promote the formation of banded microstructures, the finishing rolling temperature was controlled at 880 °C. Subsequently, the plates were uniformly cooled to the designated coiling temperatures using a water curtain



**Fig. 1.** (a, d) OM, (b, e) SE-SEM, and (c, f) EBSD photos of (a ~ c) IH650 steel and (d ~ f) IH450 steel. P: Pearlite, F: Ferrite, B: Bainite, M: Martensite, ND: Normal direction, RD: Rolling direction.

laminar flow system. To induce distinct phase distributions within the banded structures, coiling was conducted at 650 °C and 450 °C, respectively, each held for 2 h.

## 2.2 Mechanical testing

Uniaxial tensile tests were conducted at room temperature on a universal tensile testing machine (CMT5605) at a rate of 1 mm/min in accordance with the national standard GB/T 228.1-2021. Specimens were prepared in a standard dog-bone geometry, featuring a gauge length of 25 mm and a width of 6 mm, with their longitudinal axis oriented parallel to the rolling direction. Hole expansion testing (HET) was performed on a sheet metal forming test system (BUP60) following the ISO 16630 standard. Test specimens were square sheets measuring 90 mm × 90 mm, extracted from hot-rolled steel plates. To eliminate the influence of surface oxides, specimens were mechanically polished prior to testing. A hole of 10 mm in diameter ( $D_0$ ) was punched at the center of each specimen. Given the final thickness was less than 2 mm post-polishing, a punching clearance of  $12 \pm 2\%$  was adopted in accordance with ISO 16630 recommendations.

Hole expansion was conducted using a 60° conical punch with the burr side of the hole facing upward away from the punch tool to avoid mechanical contact, at a punch speed of 0.2 mm/s. A clamping force of 50 kN was applied to secure the specimen and prevent displacement during deformation. The test was terminated when a crack completely propagated through the sheet thickness. A minimum of five parallel tests were conducted for each condition to minimize HER variability. The HER was

calculated using the formula:  $HER = (D - D_0) / D_0 \times 100\%$ , where  $D$  is the final diameter of the expanded hole and  $D_0$  is the initial punched diameter. The reported HER values represent the arithmetic mean of the repeated tests.

Interrupted HET was implemented to characterize the evolution of microstructure and morphology during progressive deformation. Punch displacement was selected as the interruption variable due to its precise mechanical controllability. The overall deformation window was estimated based on the punch displacement range observed in more than five full HETs, spanning from initial contact to final fracture. An interruption point corresponding to approximately two-thirds of the total displacement was selected for targeted observation. Given the pronounced variability in the punching condition of hole edges, the deformation state during interrupted tests exhibited considerable fluctuations, thus complicating reproducibility across samples. To maximize data yield and minimize sample consumption, the actual interruption timing was dynamically adjusted during real-time monitoring. Specifically, the test was halted upon the initial appearance of damage at the hole edge. This strategy allowed for the effective capture and analysis of partially propagated cracks that had not yet penetrated the full sheet thickness.

## 2.3 Microstructural characterization

Specimens for microstructural characterization were sectioned from hot-rolled sheets via wire electrical discharge machining, yielding dimensions of 8 mm × 10 mm × thickness. The rolling direction (RD) and normal



**Table 1.** Tensile properties and hole expansion ratio of IH650 steel and IH450 steel.

| Steels | YS (MPa)     | UTS (MPa)    | TE (%)     | PSE (GPa%) | HER (%)    |
|--------|--------------|--------------|------------|------------|------------|
| IH650  | $651 \pm 2$  | $788 \pm 3$  | $26 \pm 2$ | 20.5       | $34 \pm 2$ |
| IH450  | $943 \pm 12$ | $1419 \pm 5$ | $12 \pm 2$ | 17.0       | $9 \pm 2$  |

direction (ND) planes were selected for analysis. Surface preparation involved sequential grinding with silicon carbide papers from 400 ~ 7000 grit, followed by electrolytic polishing in a solution composed of 20% perchloric acid and 80% ethanol to eliminate mechanical damage and remove surface residual stress. Microstructure was revealed by etching with 4 vol.% Nital for 5 s ~ 10 s.

Macroscopic fracture morphology and optical microstructures were examined using a laser confocal microscope (OLS4100). Scanning electron microscopy (SEM) was conducted on a ZEISS ULTRA 55 thermal field emission microscope in secondary electron (SE-SEM) imaging mode at an accelerating voltage of 20 kV and a working distance of 15 mm ~ 20 mm. Electron backscatter diffraction (EBSD) analysis was carried out using a FEI Quanta FEG 450 thermal field emission SEM equipped with an EBSD detector, operating at 20 kV with a step size of 0.06  $\mu\text{m}$ . The phase volume fractions were determined through image analysis in ImageJ (version 1.54 g, Java 1.8.0) based on grayscale or color contrast, and EBSD data were post-processed using AZtecCrystal software. A minimum of five regions per sample were analyzed to ensure statistical reliability.

## 3 Results and discussion

### 3.1 Microstructures

Figure 1 displays the optical microstructures (OM), SE-SEM images, and EBSD maps of steels isothermally held at 650 °C (IH650 steel) and 450 °C (IH450 steel). The EBSD maps are presented with overlays of band contrast (BC), kernel average misorientation (KAM), and grain boundaries (GB). As shown in Figure 1a and 1b, well-defined banded structures were successfully developed via the hot rolling process. Pearlite is a biocrystal composed of ferrite and cementite [22], appears dark under OM due to cementite aggregation within its micron-scale lamellar spacing. In SEM images, ferrite is shown in dark contrast, while cementite manifests as bright, rod-like particles. Due to resolution constraints in EBSD, the internal features of pearlite are not distinctly resolved. Therefore, with the help of GB, BC, and KAM identification [23], the pearlite grains are comprehensively determined by grain morphology size, image quality, and misorientation fluctuation in grains.

In IH650 steel, the microstructure comprises approximately  $33 \pm 3\%$  pearlite and  $67 \pm 3\%$  ferrite, with minor spheroidized block-like cementite particles observed at ferrite grain boundaries. These phases align preferentially along the rolling direction, forming a pronounced banded morphology. IH450 steel primarily consists of bainite and martensite, with volume fractions of  $32 \pm 7\%$  and  $68 \pm 9\%$ , respectively. The bainitic ferrite substructure and

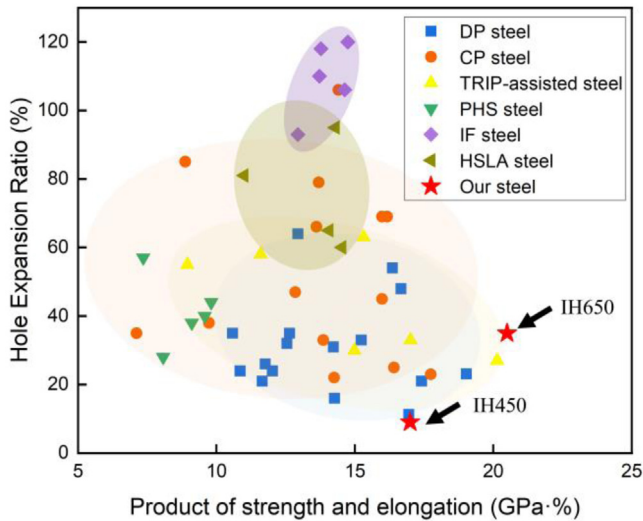
second-phase islands contribute to the prevalence of low-angle grain boundaries. Martensite regions are marked by significantly low BC values, appearing as dark zones in EBSD maps. Austenite content was consistently below 1% in both steels and was thus excluded from subsequent analysis.

Based on the continuous cooling transformation characteristics, ferrite and pearlite, as well as bainite and martensite, form within adjacent transformation regions. As a result, the mechanical property gradients between constituent phases in IH650 and IH450 are relatively modest. The minimal hardness contrast potentially facilitates more uniform deformation and is conducive to improved hole expansion performance.

### 3.2 Mechanical properties

Table 1 lists the yield strength (YS), ultimate tensile strength (UTS), total elongation (TE), product of strength and elongation (PSE), and HER in punching hole conditions of IH650 steel and 450 °C steel. The IH650 steel exhibits a favourable balance between strength and ductility, with a PSE value of approximately 20.5 GPa·%.

Figure 2 presents the correlation between HER and PSE of the experimental steels used in this work and the AHSS plates of other researchers under the punching hole condition, including DP steel [24–29], CP steel [24, 30, 31], TRIP-assisted steel [24, 29], PHS steel [24, 27, 29], IF steel [27] and HSLA steel [27]. For steels exhibiting excellent hole expansion ratio, such as IF, HSLA, and CP grades, the product of strength and ductility generally lies within 10 ~ 17 GPa·%. In contrast, steels with relatively higher strength–ductility products, including CP, TRIP, and DP grades, exhibit hole expansion ratios in the range of 10 ~ 40%. Evidently, the relationship between the strength–ductility product and hole expansion behavior is not characterized by a simple trade-off. Instead, steels with moderate strength–ductility levels tend to achieve optimal hole expansion performance, whereas both extremes in strength–ductility are associated with only moderate expansion capacities. From a compositional and microstructural standpoint, the data points corresponding to IF steel are more compactly distributed, whereas those of CP, TRIP, and DP steels exhibit greater dispersion, reflecting pronounced performance variability. Such dispersion arises not merely from the limited number of samples analyzed but is intrinsically linked to the broader property range inherent to multiphase steels. Variations in the morphology, spatial distribution, and volumetric fraction of the constituent phases—tailored to meet diverse application requirements—result in significant fluctuations in both mechanical response and hole expansion characteristics. It can be seen that IH650 steel not only demonstrates



**Fig. 2.** Ashby map in terms of HER vs. PSE under the punching hole condition of various AHSS steels.

excellent mechanical properties but also offers a good combination of strength-ductility and hole expansion performance compared when benchmarked against these commercial AHSS grades. The combination of pearlite and ferrite ensures the plasticity while also ensuring the strength due to the enhancement of microalloying.

In contrast, IH450 steel demonstrates high strength but suffers from reduced ductility and limited hole expansion ability. Although its dual-phase structure, consisting of bainite and martensite, theoretically promotes crack resistance during hole expansion due to similar mechanical responses, the experimental results indicate otherwise. This suggests that the effectiveness of microstructural homogeneity as a strategy for enhancing hole expansion performance is constrained when hard, low-temperature transformation phases dominate the microstructure, no matter what sophisticated structural design has been made. Ultimately, the intrinsic characteristics and phase constituents—particularly the framework composition—play a decisive role in governing hole expansion behavior.

### 3.3 Quantification of hardening in the shear affected zone

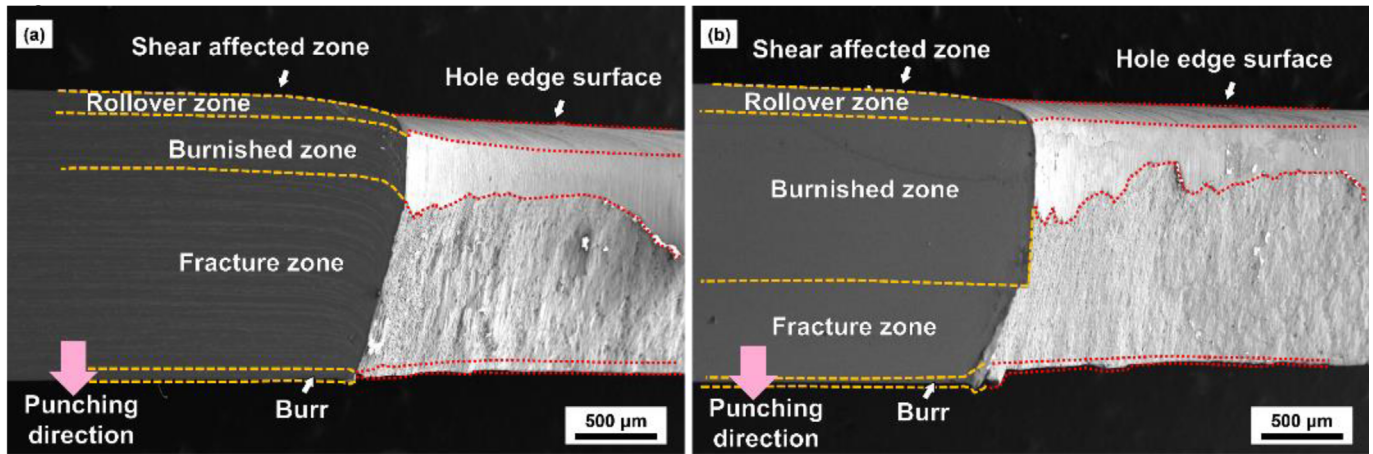
As shown in Figure 3, the morphology of the hole edge to the matrix (outlined by the yellow square dot line) and the inner edge surface of the hole (outlined by the red circle dot line) of IH650 steel and IH450 steel after punching. In the first step of the hole expansion experiment, severe shear deformation in the center of the plates will form a localized deformation zone near the hole, called the shear affected zone (SAZ) [32]. As shown in Figure 3, it typically comprises four distinct subzones as a rollover zone, a burnished zone, a fracture zone, and a burr. The presence of the SAZ reflects pre-existing strain and hardening induced during punching, which in turn significantly alters the material's initial condition prior to hole expansion. It should be emphasized that observations from three parallel specimen sets reveal that the predominant variation in

hole-edge morphology after shearing occurs in the relative proportions of the SAZ subregions through the thickness direction. This variation is considered to be strongly correlated with the local microstructural heterogeneity within the sheared zone and is characterized by pronounced fluctuations. Nevertheless, the inherent morphological characteristics of each subregion remain essentially consistent, thereby ensuring that the subsequent detailed analysis of their morphologies is not compromised.

This pre-strain and hardening play a crucial role in the subsequent deformation behavior and affect the HER, a key index for evaluating edge cracking sensitivity. Since different microstructures exhibit distinct work hardening responses during punching, it becomes necessary to quantify this punching-induced hardening. In this study, the degree of deformation-induced damage within the SAZ was assessed via microhardness profiling [33]. This subsection first focuses on the hardening gradient from the punched edge to the base material.

Figures 4a–4d presents the microhardness curves of different areas of the SAZ, where the microhardness indents were applied at the center of each zone. A general decrease in hardness is observed with increasing distance from the hole edge, indicating significant work hardening concentrated near the edge that progressively relaxes toward the undeformed material. To quantitatively evaluate this effect, a hardening characteristic value (HCV) is defined following the approach in reference [19],  $HCV = 100\% \times (H_n - H_0) / H_0$ , where HCV represents the normalized material hardening condition, %;  $H_n$  denotes the microhardness at each indent, HV;  $H_0$  represents the baseline hardness of the as-received steel without the deformation, HV. The HCV distribution was visualized using grayscale maps in Figures 4e and 4f, where lighter areas indicate the unaffected matrix, and darker regions represent progressively higher levels of hardening. It is worth mentioning that the proportion of each SAZ zone, that is, the thickness of each zone shown in Figures 4e and 4f is not fixed but varies depending on processing clearance, punching tool quality, and even local structure features. This can be further corroborated by the SEM micrographs of the hole edge surface presented in Figure 3, in which the relative proportions of the burnished zone and the fracture zone display a pronounced variation. Therefore, the thickness of each zone shown in Figures 4e and 4f only represents the characteristics of this specific sampling position, and the discussion of this factor will be ignored in this section.

As depicted in Figures 4a–4d, IH650 steel demonstrates a pronounced hardness gradient, with hardness decreasing sharply from the edge toward the specimen interior. Conversely, IH450 steel exhibits a comparatively uniform hardness distribution, particularly across the rollover zone and fracture zone, where the hardness values fluctuate around the base level rather than following a gradient. Such fluctuation is ascribed to the banded structural heterogeneity of the strip, wherein the underlying soft and hard phases beneath the indentation site contribute differentially to the measured response. Figures 4e and 4f further delineate the extent of hardness gradient reduction. The results reveal that the most severe hardening in IH650 steel



**Fig. 3.** Morphology of the shear affected zone (SAZ) and the hole edge surface of (a) IH650 steel and (b) IH450 steel after punching.

occurs within the fracture zone, reaching 57% above the base hardness, with a hardening-affected zone width of approximately 600  $\mu\text{m}$ . In contrast, IH450 steel exhibits hardening predominantly within the burnished zone, with an affected width of about 800  $\mu\text{m}$ . Furthermore, the overall hardening intensity of IH450 steel is markedly lower, as reflected by the diminished variation in hardness values and the correspondingly lighter grayscale representation. This leads to an intriguing observation: IH650 steel, despite its lower base hardness ( $\sim 270$  HV) and superior ductility ( $\sim 26\%$  TE), exhibits a more distinct hardening gradient. Conversely, IH450 steel, characterized by higher base hardness ( $\sim 403$  HV) and limited ductility ( $\sim 12\%$  TE), shows minimal gradient development. These findings suggest an inverse relationship between the punching hardening gradient and the inherent hardness or ductility of the material. While the hardening gradient generally signifies a local loss of deformability—typically considered detrimental to HER—the experimental results reveal that IH650, which experiences more severe punching-induced hardening, actually achieves a higher HER. Therefore, it can be inferred that the hardening gradient alone is not the decisive factor governing hole expansion behavior. To elucidate the mechanisms influencing HER, it is essential to further investigate the geometric and morphological characteristics of the punched edge, especially those related to SAZ configuration. Additionally, the current results show no direct evidence linking the presence of banded structures to variations in HCV.

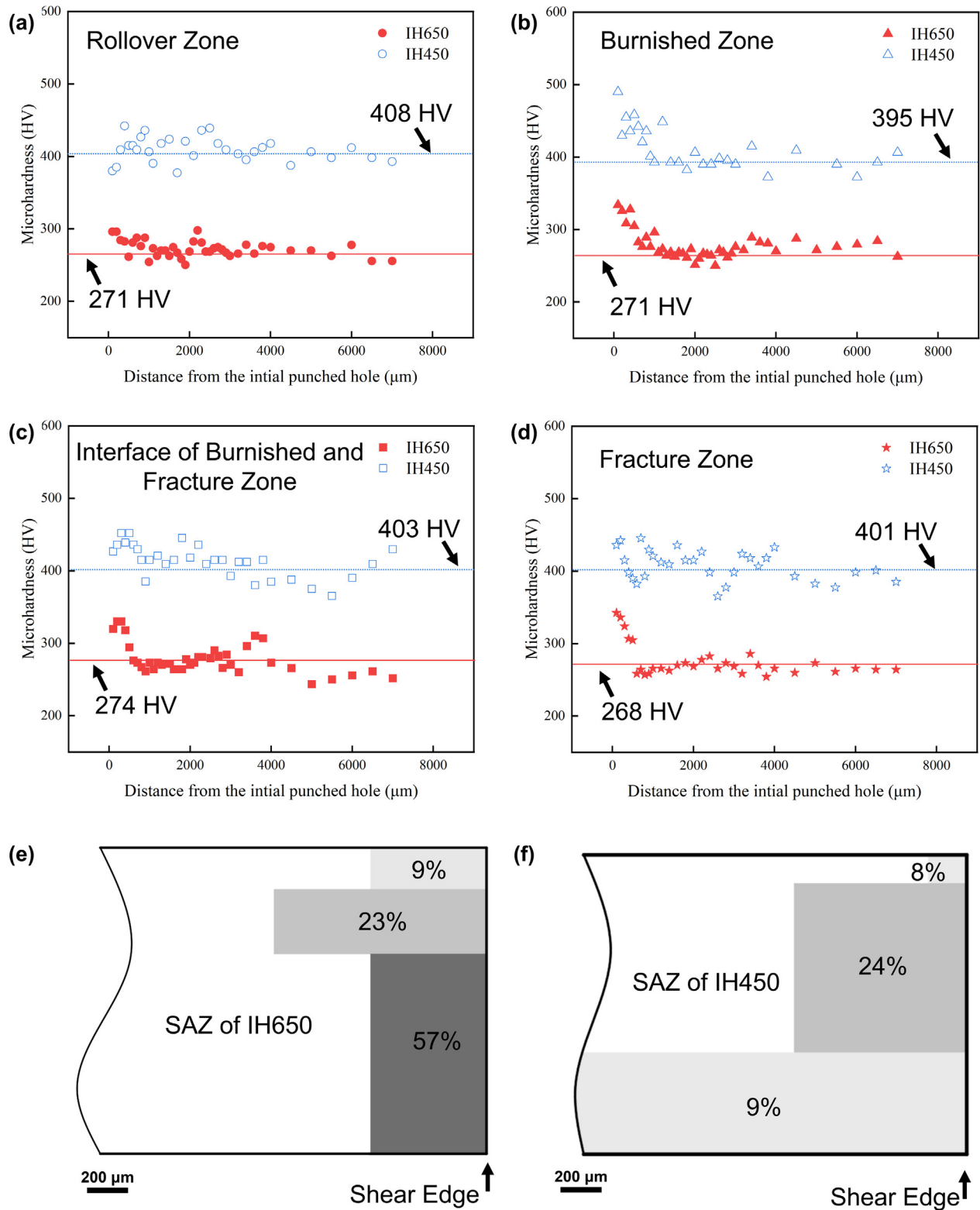
### 3.4 Morphology analysis of the shear affected zone

Figure 5 presents representative SEM images of various regions within the SAZ of IH650 steel and IH450 steel, with each observation point clearly labeled. In the rollover zone of the IH650 steel, the cleavage surface at the position of Figure 5a1 is a brittle fracture indicative of brittle failure induced by severe shear deformation. In the burnished zone, as shown in Figure 5a2, the microstructure adjacent to the hole edge exhibits a pronounced streamlined morphology (marked by the yellow square dot line),

signifying severe plastic deformation aligned with the punching direction (i.e., the sheet normal direction). This streamlined region extends approximately 25  $\mu\text{m}$  in width, accounting for roughly 2% of the hardening distance within the burnished zone. Toward the undeformed matrix side, the streamline orientation gradually shifts, ultimately aligning with the rolling direction (perpendicular to the normal direction), as more clearly illustrated in Figure 5a. The heavily deformed streamlined structure in the burnished zone facilitates void formation at the interface between ferrite and the blocky cementite. These voids are preferentially aligned and interconnected along the deformation streamlines, forming initial damage left near the hole edge.

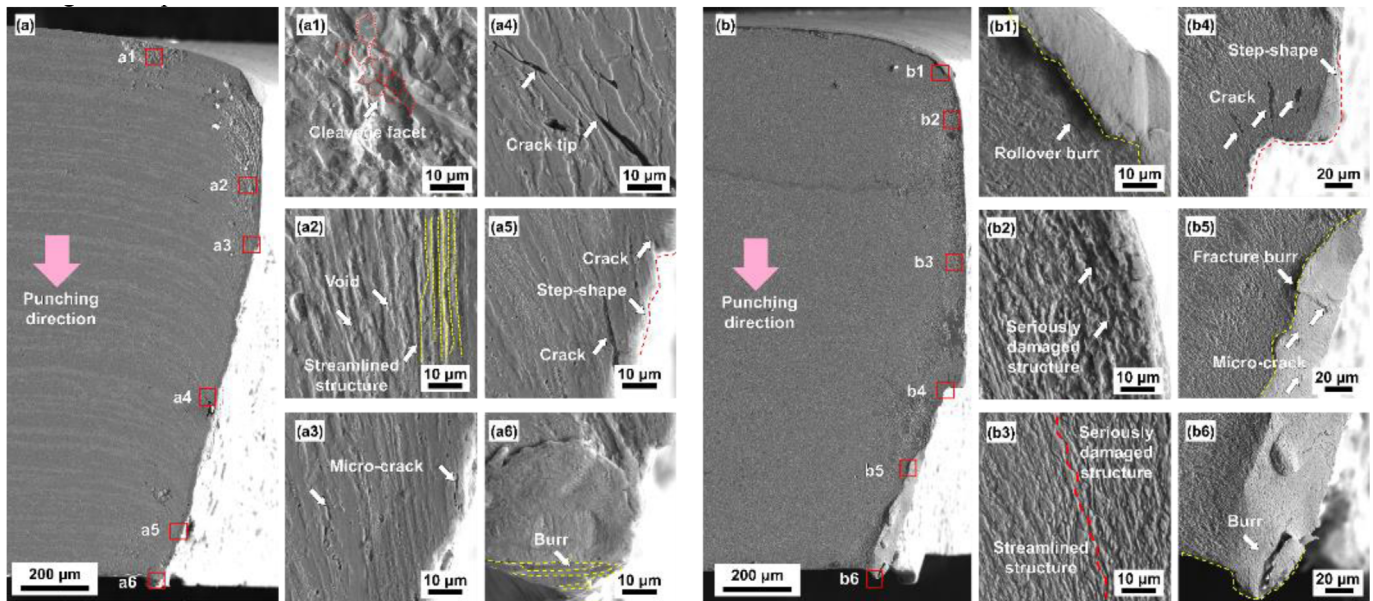
The position of Figure 5a3 is the interface of the burnished zone and the fracture zone, similar streamlined deformation is evident, along with microcracks propagated via interconnected voids. In Figure 5a4, the tip of a crack within the fracture zone is captured, where the crack propagates into the matrix along the pearlite-ferrite interface. This crack likely originates from the hardened microstructure near the hole edge within the fracture zone, as suggested by the damage morphology in Figure 5a5, which reveals a step-shape contour pattern. The step-shaped contour, induced by local microstructural hardening and damage, generates stress concentration caused by the geometric shape of the steps, which promotes crack initiation and subsequent propagation along the streamlined structure. Furthermore, the burr zone in Figure 5a6 displays classical features of microstructural delamination and pronounced hardening, and is generally regarded as the most severely damaged area of the SAZ.

In summary, for IH650 steel, beyond the severe damage in the burr zone, the step-shape features and cracks originating at the interface between the burnished and fracture zones represent the most serious morphological features of the SAZ. The presence of a banded microstructure exerts a significant influence on these morphological characteristics. In particular, the emergence of the streamlined deformation structure facilitates the coalescence of voids and the redirection of crack propagation into the matrix interior, suppressing normal-directional fracture expansion.



**Fig. 4.** Microhardness curves of SAZ from hole edge to matrix in (a) rollover zone, (b) burnished zone, (c) interface of burnished zone and fracture zone, and (d) fracture zone; schematics of hardening in SAZ of (e) IH650 steel and (f) IH450 steel.





**Fig. 5.** SAZ morphology SEM photos of (a) IH650 steel and (b) IH450 steel, the positions of (a1 ~ a6) and (b1 ~ b6) are framed in (a) and (b), respectively.

According to the previous research [19], under milled-hole conditions (i.e., in the absence of SAZ and hole-edge hardening gradients), the streamlined structure plays a decisive role in governing failure morphology and fracture modes during hole expansion. Therefore, the contribution of such banded ferrite–pearlite-induced streamline structures to hole expansion behavior merits further investigation. It is reasonable to hypothesize that the interfacial morphology at the boundary between the burnished and fracture zones is a dominant factor affecting the damage after punching, with the streamlined structure critically influencing crack propagation. Moreover, phase boundaries—such as those between ferrite and cementite, and ferrite and pearlite—may serve as preferential sites for void nucleation and damage accumulation, thus playing a vital role in the subsequent deformation during hole expansion.

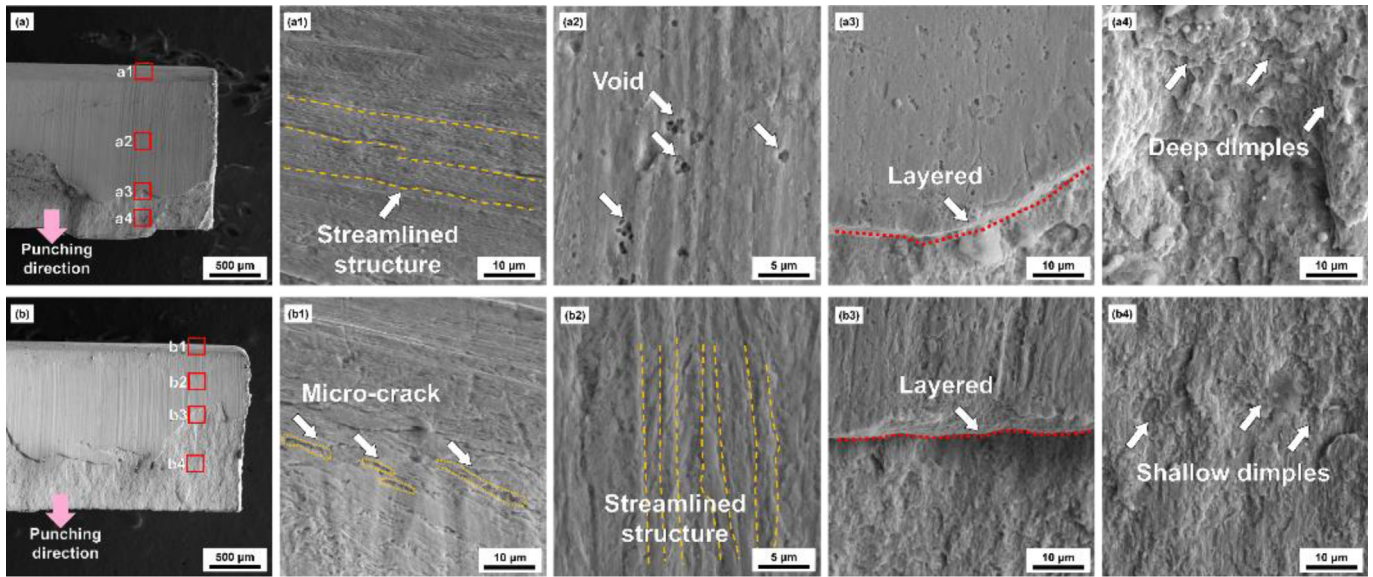
For IH450 steel, in addition to the burr and microstructural delamination in the burr zone as shown in Figure 5b6, similar deformed structure and microcracks are observed in the rollover zone of Figure 5b1 and at the edge of the hole in the fracture zone of Figure 5b5. This behavior is closely associated with the inherent micro-hardness of the material. The bainite–martensite microstructure exhibits limited capacity for accommodating plastic deformation due to the intrinsic brittleness and hardness of its constituents. As shown in Figure 5b2, a heavily deformed region is present; however, unlike the well-aligned streamline structure observed in IH650 steel, the deformation structure is distributed around the island-like second phase in bainite, rather than strictly along the grain boundary between bainite and martensite. This is because bainite is composed of bainitic ferrite and island-like second-phase martensite-austenite (MA) constituents. The interface between these high-hardness MA and the comparatively softer bainitic ferrite acts as the boundary

between severe and mild plastic deformation regions. Toward the matrix side, where the punching-induced hardening effect weakens, a streamline structure reappears—this time aligning with the phase interface between bainite and martensite, as depicted in Figure 5b3. In this region, step-shape morphology at the boundary between the burnished and fracture zones is clearly visible, accompanied by microcracks. Notably, the interface between brittle blocky cementite and ferrite in the IH650 matrix is theoretically a weak point, where voids should typically nucleate due to particle decohesion. However, no such voids were detected in the IH450 matrix. This absence is likely attributable to the high and relatively uniform hardness of the bainite–martensite matrix, which lacks distinct geometric or mechanical mismatch at phase interfaces that would otherwise promote void formation.

In summary, as with IH650 steel, the primary damage morphology for IH450 steel also involves step-shape features and microcracks at the interface between the burnished zone and fracture zones. Additionally, the increased burr formation across different regions of the SAZ contributes to significant edge degradation, which is reasonably expected to impair the steel's subsequent hole expansion capability. Importantly, the presence of a bainite–martensite banded structure does not exhibit a notable impact on the morphological characteristics of punching damage. Combined with the earlier analysis in Section 3.2, it can be concluded that microstructural distribution plays a secondary role relative to the intrinsic deformation compatibility of the constituent phases. This conclusion is supported by mechanical indicators such as strength, total elongation, and hardness.

The foregoing discussion focused on the damage and hardening morphology observed on the normal-rolling (ND–RD) planes near the hole edge within the SAZ.





**Fig. 6.** Hole edge surface morphology SEM photos of (a) IH650 steel and (b) IH450 steel, the positions of (a1 ~ a4) and (b1 ~ b4) are framed in (a) and (b), respectively.

However, considering the criteria for assessing hole expansion failure, it is also essential to examine the hole edge surface, i.e., the plane formed by the normal direction and the circumferential direction (ND-CD). This will provide a more direct understanding of the geometric and material damage induced by punching. Therefore, in the subsequent section, detailed characterization of the hole edge surface will be performed to complete the three-dimensional evaluation of phase-related and banded structure effects on post-punching damage and performance.

### 3.5 Morphology analysis of the hole edge surface after punching

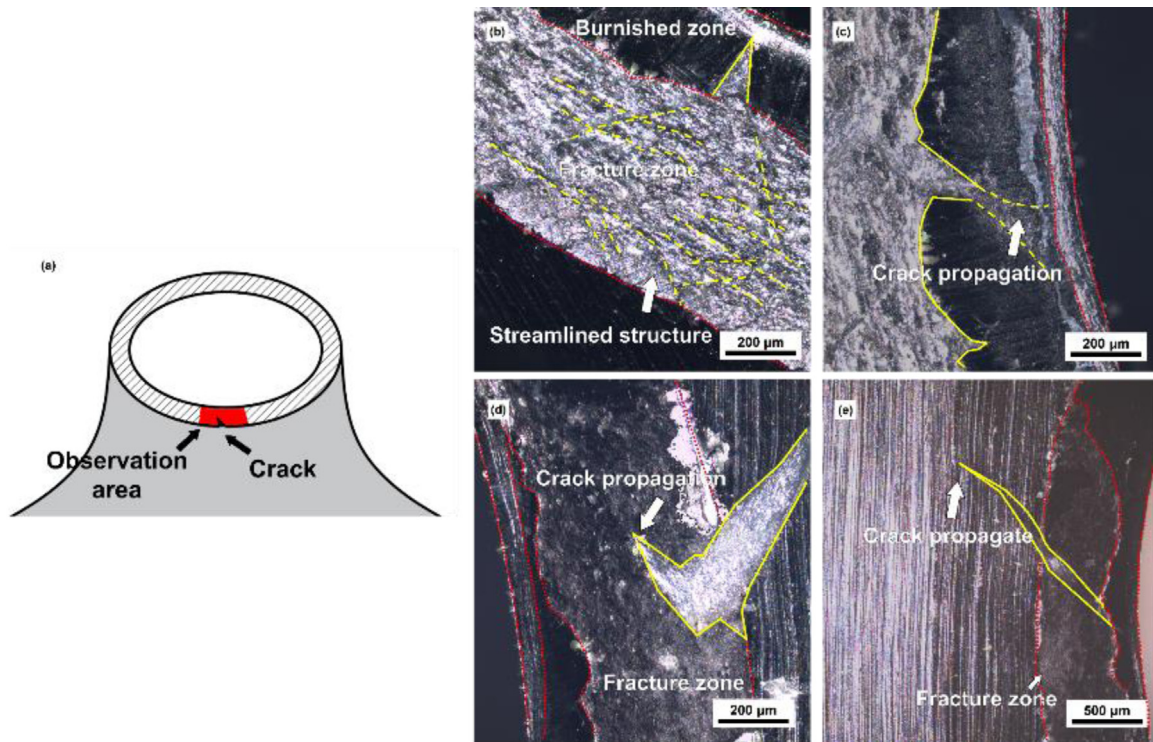
Figure 6 presents representative SEM images of the hole edge surfaces in IH650 steel and IH450 steel. When integrated with the observations from Figure 3 and 5, it can be confirmed that the rollover zone is a curved region formed due to punch-induced extrusion. In IH650 steel, as shown in Figure 6a1, this region displays an uneven, plastically deformed streamlined structure when viewed in two dimensions. In contrast, as shown in Figure 6b1, IH450 steel exhibits microcracks that arise from interconnected voids, likely due to localized strain incompatibilities. Notably, several island-like features are visible adjacent to or embedded within the voids, presumed to correspond to bainitic second-phase constituents.

The burnished zone, as shown in Figure 4, typically forms a relatively flat surface at the hole edge. As can be seen in Figure 6a2, in ferrite-pearlite steel, shallow pits are distributed across this region, suggesting localized damage or particle detachment. In bainite-martensite steel, the surface of the burnished zone is completely covered by streamlined structures along the punching

direction (thickness direction, normal direction), as shown in Figure 6b2. These streamline structures represent a non-uniform surface topography with roughness. The recessed “gullies” along the streamlines serve as potential sites for crack initiation and provide low-resistance pathways for crack propagation under applied stress. As such, the presence of these features indicates a reduction in local deformation capacity. From an energy perspective, these non-uniformities may enhance energy absorption during deformation, thereby increasing the resistance to crack growth and benefiting hole expansion to some extent [34].

Figure 6a3 and 6b3 shows the morphology of the interface between the burnished zone and the fracture zone. This area appears as a distinct, irregular dividing line that separates the two regions sharply. As previously noted in Figure 5, this interface corresponds to a step-shape morphology in the ND-RD plane, indicating a non-continuous surface discontinuity in three-dimensional space. This structural irregularity is the most geometrically inhomogeneous feature across the entire hole edge, and its presence accounts for the high propensity for microcrack formation observed at this site, as shown in Figure 5a5 and 5b4.

The fracture zone displays an irregular surface, characterized by distinct fracture features and surface delamination. As shown in Figure 6a4, numerous dimples smaller than  $1\ \mu\text{m}$  are observed in IH650 steel, indicative of ductile fracture. These dimples exhibit asymmetry—sharper on the upper edge and more deformed on the lower edge—consistent with the directionality of the punching load. In contrast, IH450 steel lacks well-defined dimples and primarily shows shallow voids or pits, indicative of a lower ductility fracture mode in Figure 6b4. Additionally, the fracture surface of IH650 steel exhibits greater surface undulation compared to the relatively smoother surface observed in IH450 steel.



**Fig. 7.** (a) Schematic diagram of the sampling position of the hole edge surface morphology during the interrupted HET, and OM images of (b, c) IH650 steel and (d, e) IH450 steel.

In summary, excluding the burr, which is considered a fully damaged region with negligible deformability, the burnished–fracture interface represents the most significant geometric discontinuity at the hole edge and likely serves as a critical initiation site for damage during subsequent deformation. Across all observed morphologies, no distinct influence from the banded structure distribution was apparent on the hole edge surface features. Instead, the principal determinant of morphological variation appears to be the inherent nature of the matrix microstructure. The ferrite–pearlite matrix in IH650 steel, characterized by lower strength and greater ductility, demonstrates good deformation compatibility and toughness. Conversely, the bainite–martensite matrix in IH450 steel offers reduced toughness and limited plastic accommodation, resulting in a more brittle damage profile.

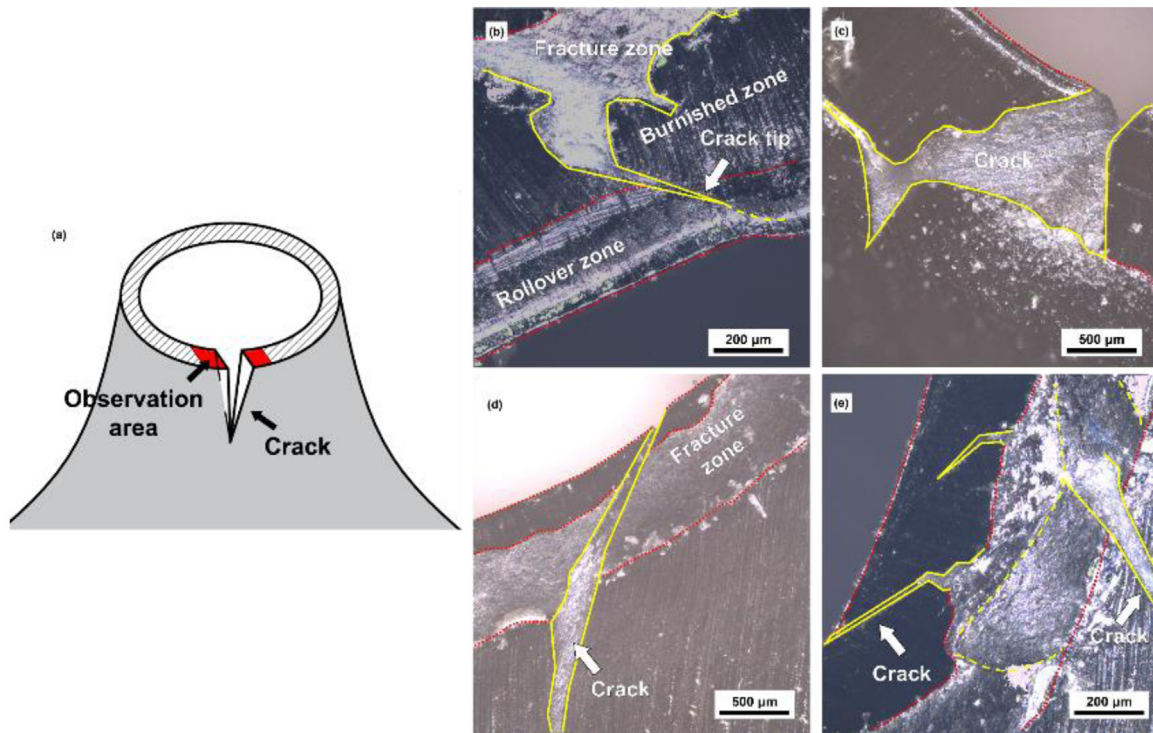
The influence of the streamlined structures—especially those in the burnished zone aligned with the sheet thickness direction—on the hole expansion behavior requires further investigation. Accordingly, the next section of this study will involve conducting interrupted hole expansion experiments, enabling direct observation of deformation evolution. Through detailed characterization of morphological changes across distinct regions during expansion, a more comprehensive understanding will be developed regarding the impact of microstructural features and their distribution on the overall hole expansion behavior.

### 3.6 Microstructure evolution during hole expansion deformation

To investigate the evolution of microstructure morphology during hole expansion, interrupted hole expansion tests were performed. First, capture the damage position of the hole edge, and then characterize the morphology of the red shadow area as shown in Figure 7a. The corresponding optical micrographs of the hole edge are shown in Figure 7b–7e. As a preliminary note, and consistent with the observations from Figure 6a and 6b, variations in the relative proportions of each deformation zone—particularly the burnished and fracture zones—are present across samples. These inconsistencies are attributed to uncontrollable process factors such as tool wear. As such, distinct cases are analyzed separately.

For IH650 steel, when the fracture zone occupies a large proportion of the hole edge, as illustrated in Figure 7b, a circumferential streamlined structure forms within the fracture zone. This morphology aligns with previously reported findings [35] and is attributed to the influence of banded microstructures. The presence of these circumferential streamlines can impede crack propagation along the thickness direction and contribute to stress redistribution, thereby enhancing damage tolerance during deformation. In contrast, when the fracture zone is less prominent, as shown in Figure 7c, no distinct circumferential streamline structure is observed in the fracture zone. Instead, cracks are initiated in the fracture zone and extend toward the





**Fig. 8.** (a) Schematic diagram of the sampling position of the hole edge surface morphology after HET, and OM images of (b, c) IH650 steel and (d, e) IH450 steel.

burnished zone. Notably, upon entering the burnished zone, the crack tip does not propagate linearly through the thickness. Rather, it exhibits a dispersed and blunted morphology (highlighted by the yellow dotted line), suggesting crack deflection and energy absorption. This phenomenon is likely related to the pre-existing voids in the burnished zone formed during punching, as shown previously in Figure 6a2.

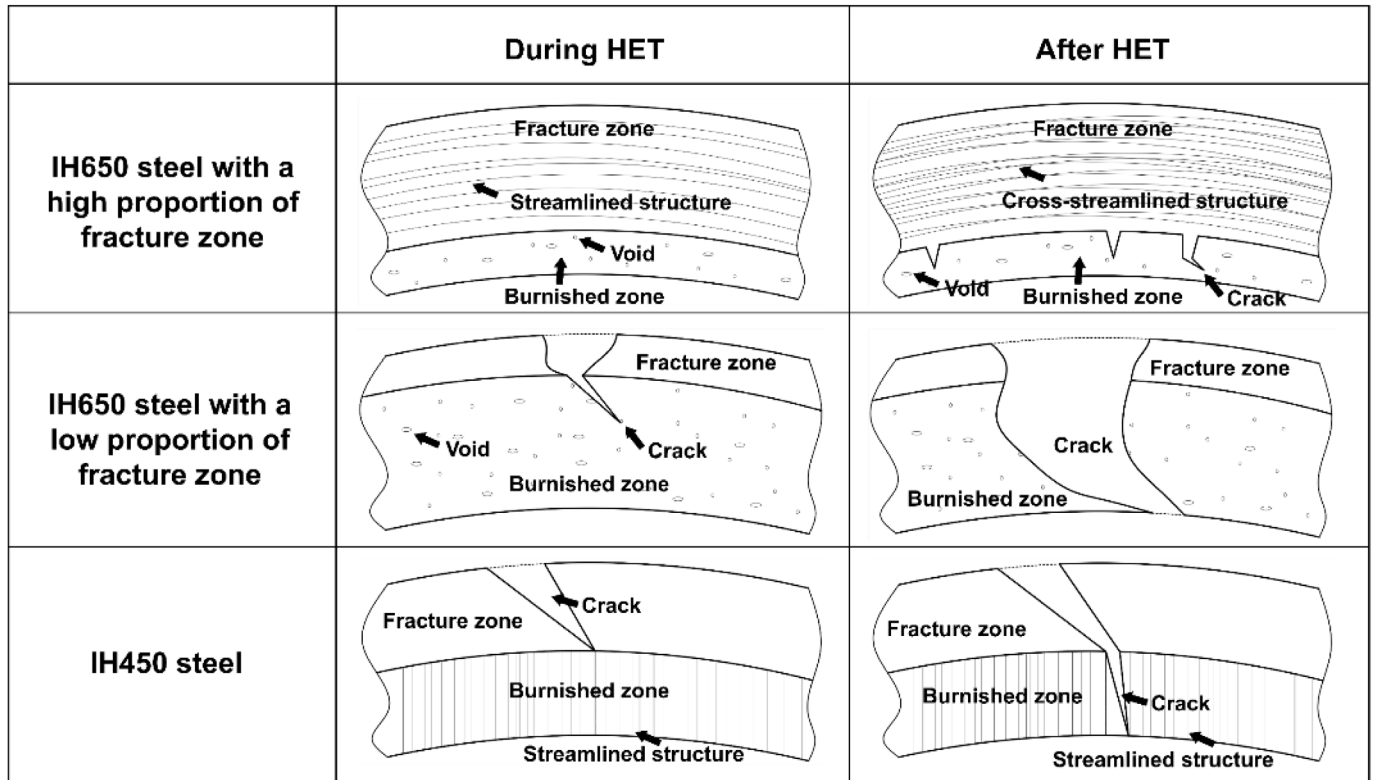
For IH450 steel, when the fracture zone is dominant, as shown in Figure 7d, crack initiation consistently occurs at the burr—the outer edge of the hole—and subsequently propagates both inward into the matrix and laterally along the fracture zone. This behavior indicates poor deformation compatibility of the bainite–martensite matrix and highlights the influence of stress concentration around the burr. Notably, no circumferential streamline structures are observed within the fracture zone. When the fracture zone is in a low proportion, as shown in Figure 7e, crack initiation still originates from the burr, extends into the matrix, and traverses the fracture zone on the opposite side. However, crack growth is arrested or significantly slowed at the interface between the burnished and fracture zones, indicating that this boundary acts as a barrier to further propagation.

Figure 8 presents the final fracture morphology of the hole edge in IH650 and IH450 steels after full hole expansion, and the schematic diagram of the characterization observation area is shown in Figure 8a. For IH650 steel, repeated testing reveals that fracture consistently initiates at regions where the fracture zone is in a low

proportion. This observation implies that a higher proportion of fracture zone, associated with the development of circumferential streamlined structures, contributes positively to hole expansion behavior. In these cases, cracks initiate at the outer edge and propagate inward toward the burnished zone. Figure 8b shows an example where the crack opening displacement exceeds  $200\ \mu\text{m}$  at the hole edge, ultimately forming a sharp-tip crack extension into the burnished zone. Figure 8c illustrates the final fracture morphology with a crack opening on the millimeter scale, indicating a significant pre-fracture warning and pronounced ductile deformation. The large crack opening displacement also suggests that failure within the burnished zone is not solely governed by classic crack tip propagation mechanics. Instead, the complex surface morphology induced by punching appears to inhibit direct crack growth. This underscores the important role of punching-induced features in altering the fracture mode and improving the damage tolerance during hole expansion.

The crack opening displacement of IH450 steel is limited to several tens of micrometers, as illustrated in Figure 8d. This observation suggests that plastic deformation is primarily localized within the fracture zone, while the surroundings exhibit minimal capacity to accommodate strain. In Figure 8e, the fracture zone exhibits tearing and localized collapse; however, once the crack advances into the burnished zone, it rapidly penetrates through the thickness direction, leading to failure. This unimpeded crack propagation is attributed to the streamlined





**Fig. 9.** Schematic illustration of the hole expansion failure mechanism of IH650 steel and IH450 steel.

structure parallel to the thickness direction introduced during punching, which acts as a preferential path for crack growth. Additionally, there is no clear evidence that variations in the proportion of the fracture zone significantly influence the final fracture morphology in IH450 steel. It is noteworthy that the hole edge, oriented at a  $45^\circ$  angle to the transverse/longitudinal direction of the sheet, serves as the primary site of repeated fracture during hole expansion deformation. Therefore, the potential influence of material anisotropy or local geometric features at the hole edge on the test results cannot be excluded.

Based on the above fracture mechanism analysis, a schematic representation of the two fracture modes is provided in Figure 9. For clarity, the figure illustrates a simplified depiction of the hole edge surface, highlighting only the burnished zone and the fracture zone. In IH450 steel, characterized by poor deformability, the proportion of the fracture zone and the design of banded microstructure distribution appear to exert negligible influence on the hole expansion behavior. Instead, the dominant factor governing deformation behavior is the intrinsic nature of the matrix microstructure. When the matrix consists of hard phases, such as bainite and martensite, the burnished zone becomes covered by streamlined structures aligned with the thickness direction during punching. These features compromise the steel's ability to resist crack propagation and degrade the overall hole expansion performance. In contrast, when the matrix comprises softer phases, such as ferrite and pearlite, voids are

generated within the burnished zone upon punching. These voids act as localized energy dissipation sites, facilitating damage accommodation and enhancing hole expansion capability.

For IH650 steel, the fracture location is typically situated near the outer edge of the hole when the burnished zone accounts for a relatively small proportion. Under such conditions, cracks are initiated within the fracture zone and propagate with a large crack opening displacement, indicating substantial plastic deformation and morphology alert prior to final failure. Conversely, when the fracture zone occupies a larger proportion, the banded microstructure distribution plays a more significant role, resulting in the formation of circumferential streamline structures within the fracture zone. These structures serve to redirect crack propagation along the circumferential direction and delay through-thickness fracture.

In summary, the development of advanced steels with enhanced hole expansion performance should prioritize the design of ductile and homogeneously distributed matrix microstructures to ensure sufficient deformation capacity. Additionally, to maximize the beneficial effects of banded microstructure distributions—particularly the formation of circumferential streamline structures—high-quality punching processes should be employed to promote a higher proportion of the fracture zone. Together, these factors provide a synergistic approach to improving the formability and damage tolerance of advanced high-strength steels during hole expansion deformation.

## 4 Conclusion

This study investigates the hole expansion behavior of hot-rolled ferrite-pearlite and bainite-martensite steels with banded microstructures, with a particular focus on the hardening response and morphological features of the hole edge surface after punching, as well as the microstructural evolution during subsequent hole expansion deformation. Two distinct damage evolution mechanisms were identified. The main conclusions are summarized as follows:

- Banded microstructures aligned along the rolling direction enhance hole expansion behavior by promoting the formation of circumferential streamline structures in the fracture zone. These structures facilitate local stress relaxation and guide crack propagation along the circumferential direction, thereby improving the steel's resistance to through-thickness fracture.
- The proportion of the fracture zone significantly affects the fracture mode. A high fracture zone ratio promotes the formation of beneficial streamline structures and delays failure. In contrast, when the fracture zone is limited, failure tends to initiate in the burnished zone but still demonstrates considerable crack opening displacement, serving as an early fracture warning.
- To fully utilize the advantages conferred by the banded microstructure, high punching quality must be ensured to maintain a sufficient fracture zone proportion, which supports the development of circumferential streamline structures during hole expansion.
- The deformability of the matrix microstructure is the primary determinant of hole expansion performance. Softer structures such as ferrite-pearlite exhibit better plasticity and damage tolerance. In contrast, harder microstructures like bainite and martensite lead to poor deformation compatibility and the formation of streamline structures aligned with the thickness direction, which accelerate crack propagation and reduce hole expansion performance.
- Punching-induced hardening is positively correlated with the hole expansion ratio and is influenced by both the matrix hardness and microstructural distribution. However, the geometric morphology of the hole edge—particularly the presence of burrs, voids, and step-shape features—plays a more dominant role in determining local formability and damage initiation.

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## Conflicts of interest

The authors of this paper declare no conflict of interest.

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This article has no associated data generated and/or analyzed.

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