Comprehensive understanding of effective parameters on edge cracking sensitivity of hot-rolled complex phase steels

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Abstract. Good stretch-flangeability is an essential property for forming complex press-formed automotive parts such as chassis, suspension and control arm components. Continuous research is ongoing in developing materials that could improve the performance of Advanced High Strength Steels (AHSS) during industrial stretch-flangeable operations. Consequently, there is a great interest in investigating the sheared edge stretchability and determining the factors, critically influencing the product edge formability. The objective of the present research is to obtain a comprehensive understanding of effective parameters on the cut-edge behaviour of Hot-Rolled (HR) stretch-flangeable Complex Phase (CP) steels. The role of microstructural damage on the edge stretchability of CP steels was evaluated employing hole punching and Hole Expansion (HE) tests. The influence of product microstructure and inclusions were highlighted. A correlation between the Lankford coefficients (‘r’ value), strain hardening exponent (‘n’ value) and Hole Expansion Rate (HER) was investigated. Finally, a new specific testing procedure combining a shearing test followed by tensile test is proposed to correlate with hole punching and HE operations and to develop in-depth understanding.

1. Introduction

In response to the rising global concern in limiting fuel consumption and CO2 emission, the steelmakers are developing new AHSS generation for automotive industry. Their use for structural components and reinforcement parts becomes unavoidable to reach required lightweight design as well as to maximize passengers’ safety and crash worthiness. Different steel qualities are proposed for final part components having attractive properties like cut-edge formability, i.e., the ability of a sheet to be stamped into a part without failure by fracture at a cut-edge. Good stretch-flangeability is an essential property for forming complex shaped automotive parts such as chassis, suspension and control arm components. There is a great interest in investigating the sheared edge stretchability and determining the most critical parameters.

Two main sources effectively affect sheared edge stretchability: the steel manufacturing process that determines the microstructure and the presence of segregation and/or inclusions; and the cut-edge features i.e. induced damage and work hardening generated during the cutting process. Misra et al. [1] identified three factors having significant influence on HE in steel sheets: the non-metallic inclusions, the condition of the hole edge and the steel microstructure. The negative impact of elongated Manganese Sulphide (MnS) or increasing Sulphur (S) content on HER for High Strength Low-Alloyed (HSLA) steels was highlighted ([1], [2]). From a microstructural point of view, the Dual Phase (DP) steels consisting of ferrite-martensite matrix exhibit poor HER values due to the presence of strong hardness...
gradient between hard and soft phases (martensite/ferrite) [3]. A separate research has shown that the stretch-flangeability of DP steels can be improved by increasing the amount of the new epitaxial ferrite (ferrite formed by transformation of austenite by epitaxial growth on retained ferrite during cooling from intercritical annealing temperature) and decreasing the quantity and the effective size of martensite islands, thus limiting the micro-crack initiation [4]. On the contrary, CP steels exhibiting homogeneous microstructure were characterized as damage tolerant and hence less edge-crack sensitive than DP steels [5]. The importance of material anisotropy on the stretch flangeability behavior was also reported by previous researches [6]. As per the study, the ‘r-value’ and more prominently the ‘n-value’ of the investigated steel grades (HR HSS exhibiting strong anisotropies) have strong impact on the localized deformation behavior, when KWI tests (HE test with flat-bottomed cylindrical punch) were performed combining different hole geometries (circular vs oval) and hole diameters.

The present study employs ISO 16630 method for HE tests [7]. Specimens of 100 x 100 mm² with a punched hole (Ø 10mm) in the center were used. The HER is presented in Eq. (1):

\[ \text{HER}(\%) = \left( \frac{d_f - d_0}{d_0} \right) \times 100 \]  

where \(d_0\) is the initial hole diameter and \(d_f\) is the average hole diameter after testing.

This paper aims at emphasizing the effective metallurgical parameters on the cut-edge behavior of HR CP steel products. The test results were analyzed as a function of various microstructural parameters, such as local heterogeneity in the matrix, importance of hard phases, impact of various particles formed during upstream steel processing, local microstructural anisotropy etc. Finally, an alternative testing methodology is presented to enhance the understanding of material behavior modelling HE process.

2. Microstructure effect

Ductile damage evolution is strongly dependent on the local microstructural morphology. Voids and mini-cracks generally develop due to decohesion at the different phases interface (such as ferrite/martensite) or within/around inclusions and particles. Previous studies have highlighted that void nucleation occurs through ferrite grain boundary decohesion in DP800 [8]. Similarly, for DP600, martensite fracture and decohesion at ferrite-martensite interface were identified as the main damage mechanisms [9]. Higher and larger martensite islands reveal to be detrimental on Formability and stretch flangeability [10]. It was reported that, if the martensite is finely dispersed into the microstructure, ferrite can accommodate more deformation, effectively delaying void nucleation and resulting in formability improvement. A conventional HR CP steel contains matrix of fine bainite, ferrite and trace amount of martensite, thus leading to low hardness gradients between the phases and better local formability. For this type of microstructure, the main damage mechanism is governed by the significant growth of voids initiated around the inclusions and carbide particles. The absence of segregation and the decreasing inclusions size and population have a positive effect on cut-edge ductility. All these aspects were investigated through microstructural observations and are discussed below.

2.1. Microstructural heterogeneity effect (including effect of hard phases)

Three different microstructures were investigated to understand the effect of phase heterogeneity on the cut-edge behavior of HR CP800 products. The primary microstructure investigation was done using SEM. In addition to SEM observation, for phase quantification, EBSD analysis was carried out where ‘mean-misorientation’ concept was applied to separate the ‘Ferrite’ / ‘Bainite’ and ‘Martensite (MA)’ fractions. The EBSD images along with individual phase fractions were presented in Figure 1. It was observed that product with primarily mono-phase structure (dominated strongly by the Bainite phase) has exhibited the highest HER value (> 100%). When the microstructure transforms towards dual-phase (mainly Ferrite and Bainite), the HER value decreases, even though MA fraction remains similar (around 1% or lower). Finally, an evolution from dual-phase to complex-phase with an increase in hard phases (MA quantity around 3-4%) further deteriorates the product ‘cut-edge’ behavior and results in the lowest HER (around 54%).
2.2. Central segregation effect
Another key parameter influencing product stretch flangeability is the presence of central segregation zone. Its presence can affect the punched hole surface by creating local grooves, as shown in Figure 2. Those grooves can facilitate the crack propagation during HE test resulting in lower HER.

![Figure 2](image1.jpg)

**Figure 2.** Damage induced by hole punching: effect of the central segregation lines; (a) crack appearance after punching on the ‘hole’ surface, (b) ‘cut-edge’ surface observation – ‘crack zone’ and (c) optical observation demonstrating crack penetration through segregation line.

3. Anisotropy
Material anisotropy effect on the localized deformation behavior around the hole edge during HE test was investigated experimentally. HE tests were carried out on HR CP800 steel punched samples marked with ‘Rolling Direction’ (RD) and positioning them differently into the testing equipment. As shown in Figure 3, irrespective of the testing orientation, cracks always occur in RD, highlighting the effect of material anisotropy on crack formation.

![Figure 3](image2.jpg)

**Figure 3.** Highlight of material anisotropy effect on HR CP800 steel

Then, KWI tests were performed. The plastic anisotropy of rolled sheet metal can be measured by Lankford parameter ‘r’:

\[ r = \frac{\varepsilon_2}{\varepsilon_3} = -\frac{\varepsilon_2}{\varepsilon_1 + \varepsilon_2} \]  (2)
Where $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_3$ are the major, minor and through-thickness plastic strains. The normal anisotropy $r_m$ and the normal strain-hardening exponent are given by Eq. (3) and (4):

$$r_m = \frac{r_0 + 2r_{45} + r_{90}}{4} \quad \text{and} \quad n_m = \frac{n_0 + 2n_{45} + n_{90}}{4}$$

Where 0, 45, and 90 represent the sample orientation in degrees with respect to the RD. ‘$r$’ and ‘$n$’ values were determined for 3% to 20% or the Uniform Elongation if it is lower.

Previous researches have highlighted possible correlation between (‘$r$’, ‘$n$’) and HER on sheared holes [11]. However, the research observations were inconclusive and contradictory. Some researchers have observed increasing HER with increasing ‘$n$’ and ‘$r_m$’ values [11], whereas an increase of HER with decreasing ‘$n$’ value was also reported [12]. Both parameters seem important for the prediction of crack initiation during HE and could have an impact on the final HER. ‘$r$’ determines the resistance to sample thinning whereas ‘$n$’ indicates the occurrence of localized deformation. To assess anisotropy effect, the through-thickness crack position on KWI samples was compared to ‘$r$’ and ‘$n$’ values in reference to RD.

![Figure 4](image_url)

**Figure 4.** Sketch describing the relation between observed crack occurrence and the corresponding ($r$, $n$) values according to crack position.

The investigation was carried out on 2 different HR CP980 products with different amounts of anisotropy and the observations were presented in Figure 5 and 6.

![Figure 5](image_url)

**Figure 5.** Correlation between crack position after HE tests and tensile parameters (‘$r$’, ‘$n$’) on anisotropic HR CP980MPa (Grade#1)
A direct correlation between HER and \((r', n')\) individually is not obvious has shown in Figure 5a and b. The Grade#1 has equivalent \(r_0\) and \(r_90\) values (the lowest ones), however, most of the cracks occurred at 90° from RD. Besides, Grade#1 has equivalent values of \(n_{45}\) and \(n_{90}\) (again the lowest ones) but no crack at 45°. A good correlation was found only by using the ratio \(r/n\) (Figure 5c). Where the lowest value of \(r/n\) appears, most of the cracks should occur in the opposite direction (90° away).

The Grade#2 presents a more isotropic behavior (\(r_0, r_{45}\) and \(r_{90}\) roughly equivalent and close to 1) compared to the Grade#2. Again, no correlation is observed between HER and individual \((r', n')\) coefficients (no cracks appear at 45° even if \(r_0=r_{45}=r_{90}\), and \(n_{45}\) is the lowest one). The ratio \(r/n\) provides the best correlation (Figure 6). \((r/n)_{0}\) and \((r/n)_{90}\) are the lowest ones and almost equal, the crack localization occurs mainly in both direction RD and 90°. Some cracks appear also at 45°, maybe since the gap between \((r/n)_{45}\) and the other ones is small. It seems that the more pronounced the differences in \(r'\) and \(n'\) values, the more distinctive is the position of the cracks. A strong correlation was also found between HER and \((r_m/n_m)\) as shown in Figure 7. HER increases with increasing \((r_m/n_m)\) values.

4. Inclusions and particles effect

The presence of hard and brittle particles such as inclusions and cementite particles in the microstructure can have a detrimental effect on the product cut-edge behavior due to particle-matrix decohesion and particle cracking. For HR CP800 product having high ‘Ti’ content, void nucleation mainly happens at TiN (Titanium Nitride) particles-matrix interfaces [13].

In the present study, HR CP800 steels with different inclusion contents and characteristics were used to investigate their impact on the HER (Figure 8a, c). Metallography analysis after HE test has revealed the presence of broken TiN at the expanded areas near the cracks and also along the crack propagation.

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**Figure 6.** Correlation between crack position after HE tests and tensile parameters \((r', n')\) on isotropic HR CP980MPa (Grade#2)

**Figure 7.** Observed correlation between HER and \(r_m/n_m\) on multiple HR CP980
path (Figure 8b). In addition, poor HER was observed for the sample with higher number of stringers and elongated CaO-Al2O3 inclusions (Figure 8d).

![Figure 8. Impact of particles on HER (HR CP800 steels); (a) HER for 2 steels with different ‘Ti’ contained particles, (b) Presence of ‘Ti’ particles on crack zone, (c) Influence of CaO-Al2O3 morphology on HER and (d) Example of elongated CaO-Al2O3 particles](image)

A root cause of damage initiation in HR CP steels comes from the ‘Hole punching’ as presented in Figure 9. SEM and TEM analysis of the punched edge of the investigated steels has exhibited the presence of significant micro voids (and sometime void coalescence) around inclusions or small carbide particles separated from the surrounding matrix, thus clearly demonstrating the initial stages of damage mechanism. Consequently, during further deformation, these small voids connect and form micro cracks, therefore, accelerating the crack propagation towards final product failure.

![Figure 9. Damage induced by the presence of inclusions and cementite particles after punching](image)

5. New methodology to simulate complete HE process
To emphasize the inclusions effect during HE test, a new testing methodology was designed to simulate each step of the Hole expansion test: hole punching and hole expanding. During the hole punching (1st step), the material is mainly sheared through the thickness. To simulate the shearing process, an in-plane shear test was considered. The main difference is that the damage (voids nucleation induced by the inclusions/particles) is through thickness oriented for the hole punching, whereas it is in-plane oriented for the shear test. However, during hole punching, the deformation solicitation is a complex phenomenon as the process involves additional bending and uniaxial tension components. For the present study, the influence of the latter parameters towards the overall deformation was considered
negligible. Tensile testing was further performed on the sheared samples to simulate the 2nd step, i.e., hole expansion during the test as shown in Figure 10.

![Figure 10. Principle of the proposed testing methodology “Shear test followed by tensile test”](image)

To establish the validity of the proposed methodology, experiments were done on two HR CP800 grades (CP#1 and CP#2) with different inclusion quantities, whereas other processing parameters remain the same. CP#1 has comparatively higher ‘Ti’ based inclusions as compared to CP#2 and hence has shown inferior average HER (around 43% HER for CP#1 as compared to around 53% HER for CP#2).

![Figure 11. Influence of a shear pre-straining of ~1: presence of a hardness gradient (a), damage occurrence by particle-matrix decohesion (b) and difference crack fracture occurrence on tensile tests, with usual sample (c) and with notched ones (d).](image)

As shown in the Figure 11, after a shear pre-straining to the amount of ~1 equivalent plastic strain, local damage was incorporated in the sample by particle-matrix decohesion. As mentioned before, tensile tests were performed on the sheared specimen, where the zone with maximum shear deformation was kept centrally within the gauge length. However, during the tensile test, for both products, the final fracture occurred by material instability (Figure 11c). The weakest points appear to be at the boundaries of the base metal and the work-hardened zone (Figure 11a, c). To further facilitate the deformation in the maximum shear zone, diffused notches were added. As shown in the Figure 11d, on the tensile sample from CP#2 (lower inclusion quantity), the fracture still has occurred outside the work-hardened zone. In contrast, the tensile sample from CP#1 has failed within the work-hardened zone. Based on the experimental results, a hypothesis can be proposed: the edge stretchability seems to be governed by the local induced work hardening combined with the sufficient local quantity of damage sites (particle-matrix voids for CP steels). Further investigations are required to confirm this assumption.

6. Summary / Conclusions
Hole punching process controls the cut-edge ductility since it induces significant damage, such as local work hardening and micro voids/cracks, near the punched edge. The sensitivity of the material during subsequent edge stretching is further influenced by the product microstructural characteristics, especially, the presence of multiple phases and the strength differential between them. The presence of inclusions such as Ti-rich, complex oxides and carbides particles are equally detrimental to the cut-edge
resistance. They act as the primary micro-void nucleation sites during punching and further facilitate the crack propagation through void coalescence and growth leading to the final fracture.

To improve the edge cracking response, a homogeneous microstructure closer to mono-phase domain and having an equiaxed grains/random textured is recommended. Reduction of segregation zone and controlling the morphology / quantity of hard phase and increasing the $r_m/n_m$ ratio could be of prime importance. A good level of steel cleanliness is essential by reducing the ‘inclusion forming” elements and further limiting the inclusions size and population. An improved cutting process could help to reduce the induced damages by decreasing edge work-hardening and micro-cracks formation.

Finally, a correlation between HER and $r_m/n_m$ ratio was observed. A new testing methodology was proposed to simulate the overall aspect of HE process highlighting the local work-hardening and damage sites influence on the product edge stretchability.

Further investigations are ongoing on to validate previous observation on additional and different HR steel grade (like Ferrite-Bainite and other CPs steels).

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