TRENDING TOPICS IN EDGE DUCTILITY RESEARCH

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ABSTRACT

Advanced High Strength Steels (AHSS) often exhibit issues in so-called edge ductility. The residual deformation available in a cut edge is limited by the cutting operation. And although better edge preparation methods are available they are not economically viable and hence shearing/cutting remains the preferred option. After years of research many influences on cut edge formability are known. For instance that the optimal clearance in AHSS is larger than that prescribed in the ISO TS16630 test standard. That sharp tools make a difference. It is also still seen that the test shows considerable scatter and difference between labs.

But there are also a number of lesser known phenomena. The delay time between cutting and forming sometimes makes a difference. The speed of cutting can make a difference. A second cut of only a fraction of material (so-called shaving) can make a significant difference but the difference depends strongly on sharpness of tools. The gradient of strain in radial direction is thought to have an influence on the results. Alternative tests to HEC may yield different ranking of materials. Links are being found between fracture toughness and HEC, and between local ductility and HEC. These links, however, do not necessarily apply to all materials.

This paper aims to give an overview of the newer findings from projects that the author is involved in as well as recent literature that has come to the attention of the author.

KEYWORDS: Edge ductility, damage, Hole expansion Coefficient

Introduction

To enable weight reduction especially in automotive, advanced high strength steels have been developed and are being developed into ever higher strengths. Where traditionally the increase in strength goes at the expense of ductility some metallurgical strategies have been found to circumvent this [1]. The best known is the dual phase steel, which has hard martensite islands in a soft ferrite matrix. As the martensite does not deform (or much less than the ferrite) the strains in the ferrite are (locally) much higher and a higher hardening rate is the result. And this causes higher uniform elongation, which is often associated with better formability. A slightly newer strategy is to incorporate retained austenite in the microstructure which transforms to martensite upon deformation introducing extra hardening and consequently, again, higher uniform elongation.

But these strategies do come at a price. The cut edge formability, also referred to as edge ductility, is less [1]. To still take advantage of the other (favourable) properties a lot of research into edge ductility is being performed. On the one hand there is the process research, looking into how cutting processes can be improved, e.g. what is the ideal clearance in a cutting process to obtain best edge ductility. On the other hand there is metallurgical research trying to understand how the material microstructure contributes to

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the sensitivity to edge cracking. This paper is not a research paper but attempts to summarise what is going on at the moment and how these researches might be linked up.

First we will look at the conical HEC and discuss its drawbacks. Then a few alternative test will briefly be treated. Then some cutting process parameters, first well know clearance effects, but there are some lesser known effects as well. Then we will see how in design of a new material the edge ductility can be accounted for.

ISO HEC

In ISO technical standard (TS) 16630 the hole expansion test using a conical punch is described. The test is schematically shown in Figure 1, it is clear there is noticeable contact stress on the edge of the material. In theory it is often assumed the stress state on the edge is uniaxial stress, but going into the bulk of the material the stress state will change rapidly. Assuming uniaxial stress, the local neck on the edge will form at a strain of:

$$\varepsilon = n \cdot (1 + r) \tag{1}$$

If the material exhibits normal anisotropy Lankford coefficient r, and Nadai hardening:

$$\sigma_y = C \cdot \left(\varepsilon_p\right)^n \tag{2}$$

The strain of *(1)* translates to a HEC of

$$HEC = \left(e^{n \cdot (1+r)} - 1\right) \cdot 100\% \tag{3}$$

However, with severe contact stresses this theory will not hold, and the gradient in deformation may also play a role [15]. The theory above is based on plasticity (instability driven) and the fracture might be more damage driven. Still author still believes the onset of necking plays a role for dual phase materials as the fracture strain for these materials may be lower than expected but is still higher than necking strain.

Experimental work with different punch geometries and simulations with both solid and shell elements [14] led to the following conclusion: “The solid simulations are able to predict the forming of a local neck quite accurately for the Nakazima and the KWI tests. The ISO test shows the stabilization due to the contact stress, but is not close to predict the onset of the local neck. There must be more phenomena that stabilize the ISO test. One of these might be the curvature, introducing geometrical stiffness, but this is very hard to test. In order to change the curvature of the blank other parameters of the test change as well, this makes it very hard to draw any good conclusions about the influence of curvature”.

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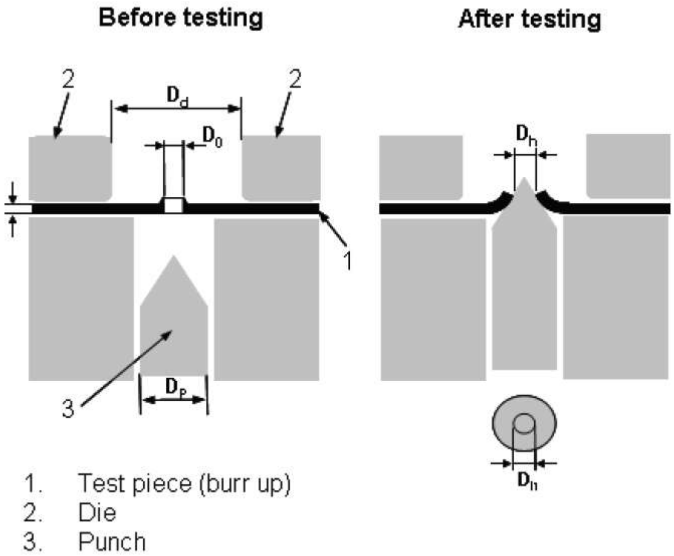

Figure 1: Schematic ISO HEC (reproduced from ISO TS 16630)

For the RFCS CuttingEdge4.0 project 4 hot rolled steels of approximately 3 mm gauge were tested. One conventional HSLA: S550MC, and 3 AHSS grades: XPF800, XPF1000 and CP800HR. The results for ISO HEC are shown in Table 1.

Table 1: ISO HEC results for 4 hot-rolled (A)HSS grades

Steel grade	Punched conical HEC, [%]	
	Mean	Standard Deviation
S550MC	55	8
CP800HR	77	10
XPF800	92	13
XPF1000	73	10

ALTERNATIVE EDGE DUCTILITY TESTS

SETi

The ISO HEC has long been viewed as not quite perfect and many attempts at correcting the deficiencies by designing another test have been undertaken. We will look firstly at Sheared Edge Tensile improved (SETi) test, [24]. It was adapted from the sheared edge tensile test procedure in [25], which itself was based on earlier publications. It was amended with DIC measurements to replace to more cumbersome stopping upon initiation of a fracture and measuring thickness. Although, admittedly the latter does not suffer from resolution issues, as DIC does.

SETi can distinguish between directions in the material, where HEC tests only pick up the weakest direction. With anisotropy in martensite morphology in DP steels this is useful information. At Tata Steel the SETi test is measured with ARAMIS and objective numbers (i.e. strain at onset of fracture) are seemingly obtained. However, the strains depend on the resolution of the DIC, although this could be standardized to make it reproducible. But they also depend on the temporal resolution: once a fracture occurs, the strain from the previous stage is taken. But by far the worst drawback is that materials which have higher edge

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ductility of the fail in the bulk first rather than on the edge. This was the problem in recent testing of 4 hot rolled (A)HSS.

The SETi test was intended to find the effect (if any) of cutting speed on edge ductility. Just like any other fracture type test there is a lot of inherent scatter and 4 repetitions were done, for 4 HR grades and 2 CR grades, with 8 speed/clearance combinations (5 clearances for slow, 3 for fast). A total of 192, but for some series it was apparent too many were missing due to various reasons and so some extra samples were tested, hence 224 in Table 2.

From the DIC measurements the classification in Table 2 was made. In a few instances the paint blistered and it was unclear when the fracture had initiated. When the sample failed near the clamping no strain could be measured. When the sample clearly failed from the middle first, no useful edge ductility data can be obtained, only a lower bound. This happened relatively often. Even more often abrupt failure occurred, which means the image before full fracture, nothing is seen. It is then not clear if failure originated from the edge or from the bulk (mid) of the sample. Finally, the useful results were less than half the samples, from left or right interpretation was trivial, for failure on both edges simultaneously, the side with lowest strain was chosen.

Table 2. Classification of SETi results.

Classification	**#**
unclear	8
no data	17
mid	56
abrupt	84
2 edges	9
left edge	25
right edge	25
Total tests	**224**

KWI

The flat nosed punch test, in the German speaking world known as KWI (for the inventors: Kaiser Wilhelm Institute) provides an alternative to the ISO HEC without the contact stress. Consequently, the values are usually somewhat lower than for ISO HEC [18], also reflected in authors own results, see Figure 2. For the 4 HR materials in Figure 2 the KWI and the conical HEC results are shown as a function of clearance. We use conical HEC instead of ISO HEC as the ISO standard prescribes the clearance as 12%, a demand we clearly violated.

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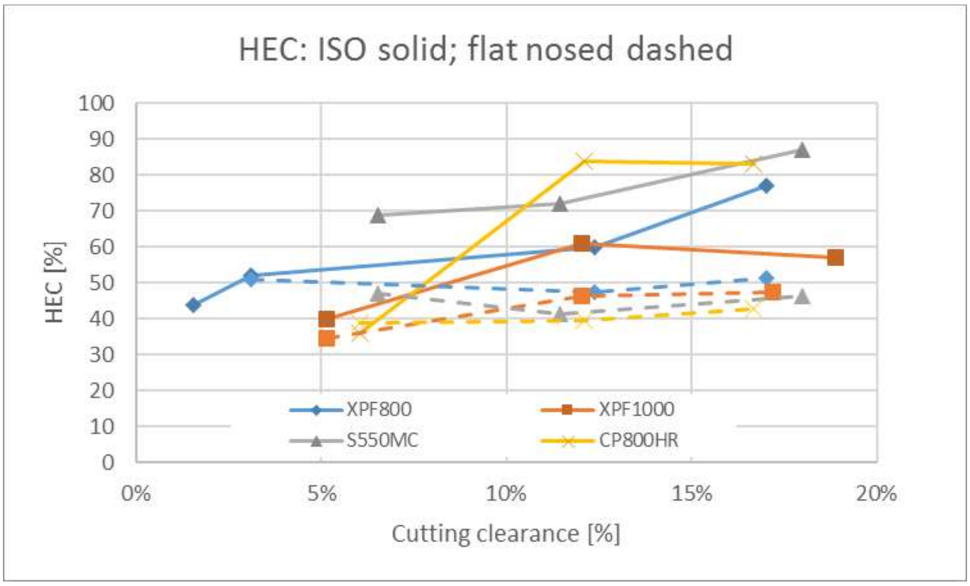

Figure 2: Results of flat-nosed punch test vs. ISO HEC

The big drawback of this test is that failure can also occur away from the edge, in the bulk of the material. Whilst the edge must be uniaxial (due to absence of bot a contact stress through thickness and a tension on the edge) further away from the hole the stress state deviates towards plane strain. And, as is well known, in plane strain deformation the strain till necking is much lower. In Figure 4 two images are show from the movie made of the flat nosed punch tests. The left image is just before fracture and necking is visible till relatively far away from the edge. The right image is just after fracture, and the fractures have grown fast. Both these observations led author to classify this specific test as **invalid**, in terms of determining edge ductility. All tests were scrutinized in this manner and the invalid results were filtered out. Consequently, Figure 3 is essentially the same as Figure 2 but instead of showing all results, it only shows the results of which we were sure they originated on the edge. The end conclusion was that for the collective of 4 hot-rolled materials the failure occurred too often in the material rather than on the edge to draw conclusions from.

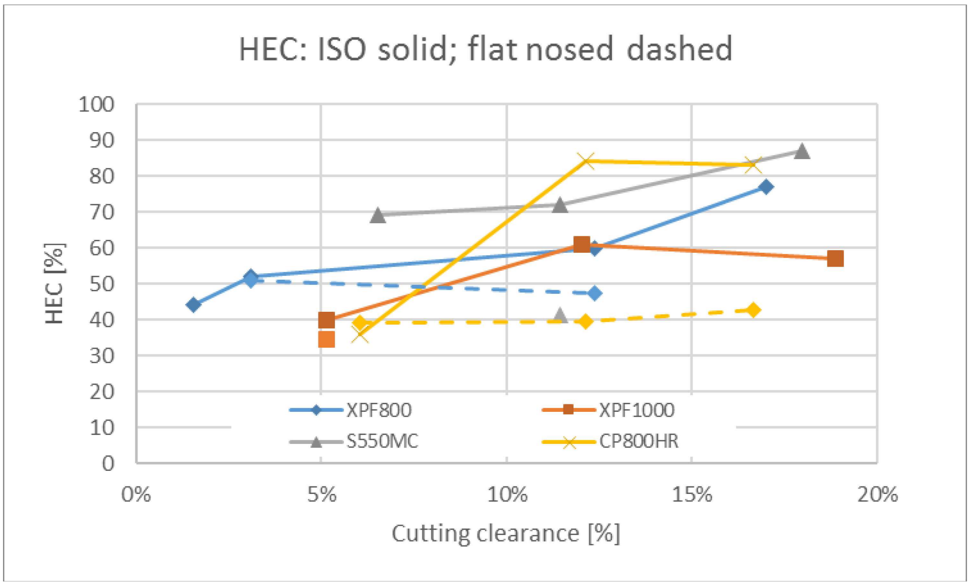

*Figure 3: Results of **valid** flat-nosed punch test vs. ISO HEC*

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Figure 4: XPF1000 in a flat nosed punch test, just before and just after fracture

EFFECTS OF PROCESS PARAMETERS

In round robin exercises often a large scatter within labs and especially between labs is found, e.g. as reported in [12]. This is probably partly due to inherent scatter because in essence it is a test for a weak spot. But the scatter between labs is likely to be explained by a number of influence not often accounted for. This paper intends to sum up those known to the author in an attempt to raise more awareness.

Clearance

The effects of clearance are well known. Too low or too high and the edge ductility drops, the sweet spot for conventional steels is around 12% and this is therefore ended up in the ISO HEC TS16630 standard. For cold rolled AHSS optimal clearance for edge ductility seems to be more like 15% as reported in a few studies, for instance most recently in [19].

Because the results are relatively sensitive to clearance, it has to be ensured that clearance as specified by the tool geometry is also obtained in practice. It was shown in [20] the too flexible cutting tooling could induce a different clearance over the circumference of the hole which causes noise on the test results. The result is dominated by the worst clearance not the intended clearance.

For hot-rolled AHSS also higher clearance than 12% is better for edge ductility, see increasing trend for all 4 materials in Figure 2 (solid lines for ISO HEC). The resolution in terms of clearance is not such that a definitive optimal clearance can be concluded from these results.

Shaving

The beneficial effect of "shaving" also known as double cutting, is by know also common knowledge. Recently however, interaction of the design of the shaving with tool wear and other parameters has been thoroughly researched by Pätzold [21]. The conclusion there is that it can help a lot in ideal circumstances but the maximum gain is not robust against changing circumstances (think: tool wear). Better to have slightly less improvement of edge ductility but be robust against changes. The sensitivity of the optimum against also indicates care has to be taken when drawing conclusions from a limited set of experiments.

Time delay

It has been observed that the time between the cutting of the samples and the (deformation) testing can play a role, [22]. Conclusions drawn on testing a limited number of materials were: CP does not suffer and DP does. And only in the presence of a zinc coating. The mechanism is not understood, although there are some hypotheses.

In recent literature different conclusions were drawn [23], as to which material is affected and which is not. This has led to a new research proposal currently being carried out at ASPPRC institute of the Colorado School of Mines.

Speed of cutting

The speed with which the material is being cut has long been suspected to be of influence, but most punching tools for HEC preparation are not designed to used in instrumented test machines. Recently this has been done nevertheless with carefully controlled cutting speed, for the 4 hot rolled materials used in CuttinEdge4.0. First attempt with the SETi test failed, as (nearly) all samples failed from the bulk of the material not the edge. But the straight edge makes it easier to see differences between fast and slow cutting (1 mm/s and 100 mm/s respectively) as depicted for CP800HR as an example, in Figure 5. The appearance of the edge is smoother for higher cutting speeds, but mainly the burnish vs. fracture ratio seems to be somewhat higher for higher cutting speed. This ratio was recently correlated to HEC by [19].

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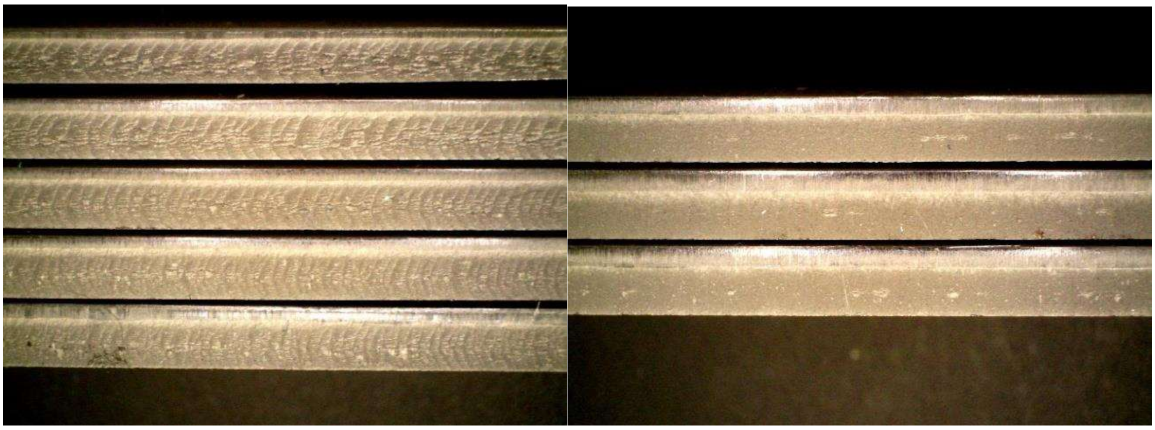

Figure 5: Left slow cutting, from top to bottom: 8%, 12%, 16%, 20%, 24% clearance
Right fast cutting, from top to bottom: 12%, 16% and 20% clearance

The results, Figure 6, show a different trend for AHSS vs. a conventional HSLA (S550MC). For medium clearance there seems to be no effect. For low clearance the effects are small, slightly better values for high cutting speed except for HSLA. And for high clearance the higher cutting speed is detrimental, again except for HSLA.
As so often happens, the effect is ambiguous and (from this limited data at least) if higher cutting speed is a benefit or a disadvantage for HEC depends on the material, the clearance and possibly on other parameters as well.

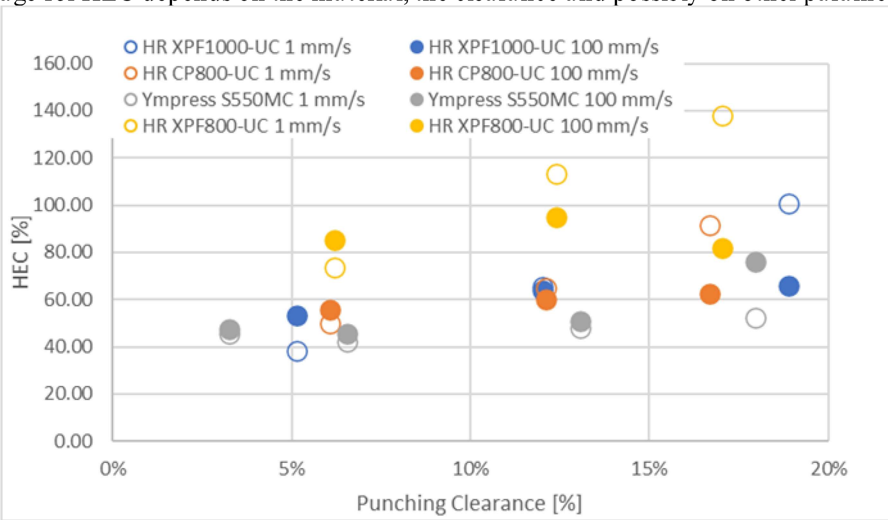

Figure 6: Effect of punching speed in ISO HEC of 4 hot rolled steels

Predeformation

Like with speed of cutting there has long been a suspicion that deformation in the sheet prior to cutting can influence the edge ductility. The effect has now been researched by Kindsmüller and the conclusions are that pre-deformation is benefitting edge ductility. This is however, in terms of loss of edge ductility when a cut hole is compared to a perfect hole, by e.g. EDM, laser cutting or drilling & reaming. For the perfect edge the edge ductility decreases with increasing pre-strain. And so it does for the cut edge, but the slope is less, so the difference between perfect edge and cut edge is getting less with increased pre-deformation.
The explanation is now sought in the fact that after pre-deformation significant hardening has occurred and further hardening due to the shearing of the edge cannot be as high as it is from virgin material. Consequently, the hardness on the sheared edge is differing less form the hardness in the bulk of the material if pre-deformation has been applied, relative to as-received material.
In ideal circumstances (sharp tool, optimal clearance) the edge ductility of the cut edge may be close to that of a perfect edge and the pre-deformation will not change that.

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THROUGH PROCESS MODEL

In the simulation world the term "Digital Twin" is a hot topic. The aim is to have the whole process chain represented in a computer model such that the influence of changes anywhere in the chain on the final outcome can be predicted. Tata Steel is participating in a programme of M2i [3] where many PhD projects (each looking a specific submodels) combine to obtain true through process model. Two projects related to edge ductility are performed in this framework. The first aims at quantifying how the DP steel microstructure impacts on the edge ductility. For this the local ductility has been chosen as a measure, see [4], motivated by literature establishing a strong correlation between edge ductility and local ductility [5][6][7], as well as fracture toughness [8]. The second project aims to quantify how the cutting process impacts on the edge ductility, and for this a new test has been developed [9] which will eventually be simulated.

The microstructural model in [4] revolves around the phase contrast between ferrite and martensite. It is concluded that the model can qualitatively confirm experimentally observed trends. Microstructures with a lower fraction of harder martensite show better global ductility but worse local ductility than those with higher fraction of softer martensite. The model characterizes global ductility by uniform strain and local ductility by a fracture strain.

But it is know that process parameters (like worn cutting tools and clearance settings) also have an impact on the edge ductility and these can obviously not be picked up by local ductility. The impact of clearance has been well documented experimentally, lately e.g. by Larour [11], but it is something which we would also like to be able to predict in a digital twin. A material might have slightly worse edge ductility compared to another material in optimal conditions but be less sensitive to a change in conditions. This, obviously, is of relevance to mass produced goods like cars.

The HEC is known to scatter a lot (see [12] but recently re-confirmed in yet unpublished ESTEP working group results), have influence of contact stresses and it cannot distinguish between directions as simply the weakest direction fails first. For all these reasons a new test has been developed, [13], which does not suffer these drawbacks. In the ISO TS 16630 HEC test the burr is positioned away from the conical punch and fracture initiates from the burr. But this is also, due to the geometry, the side with the highest strain. In [13] it was seen that even for uniform strain over the thickness the fracture still initiated at the burr side. At least for the DP800 under test. This means that somehow the burr side is the most "vulnerable" and this may have implications as to influence of clearance etc. Also, it provides a validation points for the simulations.

All this work, however, is concentrating on cold rolled advanced high strength steels. In hot rolled advanced high strength steels, which are employed in chassis and suspension components of cars, there is a similar interest in edge ductility. Tata Steel supplies single phase advanced high strength steels (XPF800, XPF1000) well as multiphase (CP800) all of which have been researched in RFCS project:"CuttingEdge4.0" of which also [10] originates. For these grades the ISO TS16630 HEC is used as standard characterization, but the relevance of a 10mm diameter hole in 3mm thick material for industry practice is questionable. So alternative tests have also been carried out.

A conclusion from [16] regarding pre-strain: "Due to the chosen procedure and the holistic view, it was possible to show that the pre-forming of CR440Y780T-DP is not to be considered as damage as in the previous explanations since the edge crack sensitivity is reduced". But the effect of different modes of pre-strain (uniaxial, plane strain or bi-axial) also depends on the cutting tool condition

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