TOWARDS MORE EFFICIENT HOLE EXPANSION TESTING

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ABSTRACT: A specially designed laboratory setup is presented allowing to efficiently conduct hole expansion tests. Various strategies to evaluate the recorded data are proposed and demonstrated by the example of a test series performed on two high strength sheet steel grades of similar strength level. In addition to the preliminary damage induced during hole preparation and the stretching of the edge during the test (including the strain gradient), the damage induced by the contact of the hole edge with the expansion tool is of utmost importance with respect to the hole expansion behavior.

KEYWORDS: hole expansion test, necking, stretch-flangeability, edge crack sensitivity

1 INTRODUCTION

Hole expansion is a simulative test to study the stretchability of sheared edges. Both, the sheet material response and the hole edge condition significantly affect the test result. On the one hand the test may be employed for the optimization of cutting technologies (e.g., fine blanking, laser cutting, etc.) for a given material to achieve highest possible edge-stretchability in subsequent forming operations. On the other hand, it is suitable for material selection (for given cutting and forming operations) and for the development of damage tolerant materials with respect to stretch-flangeability. In recent years, the required scope of hole expansion testing according to the standard ISO16630 [1] has increased significantly, which is not least attributable to the fact that the limiting hole expansion ratio is increasingly employed as failure parameter in the numerical design of sheet metal forming operations. To minimize the required experimental effort, it appears reasonable to develop a more efficient testing method and to take a critical look at the reliability of the limiting hole expansion ratio (according to [1]) as characteristic parameter assessing the edge stretchability.

This contribution presents an alternative method for hole expansion testing and evaluation, allowing fast and reliable testing and enabling a more objective evaluation of the test results. A demonstration of the proposed testing method is performed via test series of two different AHS steel grades, taking into account punched and wire-cut holes. In addition to the standard testing geometry according to ISO16630, different initial hole diameters and different cone angles are employed to clarify whether or not the limiting hole expansion ratio represents a characteristic material/edge-condition parameter describing stretch-flangeability.

2 TEST SETUP

With the purpose to improve the conventional test set-up and the testing procedure, an instrumented hole expansion test facility was conceived and constructed at the Christian-Doppler Laboratory of Material Mechanics of High Performance Alloys [2]. This special forming tool assembly was integrated into a standard tensile testing machine, s. Fig. 1.

An implemented digital camera system provides a view on the hole edge from two different directions and enables to detect through-thickness cracks and to evaluate the current hole diameter, s. Fig. 1 and Fig. 2. During each test, the video signal, the displacement of the punch and the punch force are recorded simultaneously. The axial view captures the complete hole edge and allows to identify all through thickness cracks. The tilted view allows a calibration of the camera system to quantify the current diameter of the expanded hole. The diameter of the hole is evaluated in the measurement plane defined by the axis of the hole expansion tool and the optical axes of the camera.

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Figure 3 shows typical force-displacement curves of the punch ($F$-$x$-curves). The first part of the curves (configurations A-D) is dominated by geometrical nonlinearities during elastic-plastic bending of the region close to the hole edge, until the tangent planes to the sheet surface and the cone are identical at their line of contact. During further expansion the contact between cone and specimen consists of one or more narrow conical annular areas (s. Fig. 12) and the slope of the $F$-$x$-curves is uniform (configurations D-E), primarily affected by geometrical aspects and the strain hardening of the material. With increasing damage and/or necking near the hole edge the slope of the curve decreases continuously, or the punch force drops abruptly at spontaneous failure/cracking.

### 3 EVALUATION STRATEGIES

In contrast to conventional hole expansion testing, where the punch is stopped manually when the first through-thickness crack is visible by the inspector and the hole expansion ratio is determined manually after removing the specimen [1], here the test is evaluated exclusively on the basis of the recorded data. The evaluation comprises two steps, the identification of the limiting configuration and the assessment of the corresponding limiting hole expansion ratio. For both steps different strategies are proposed in the following.

#### 3.1 LIMITING CONFIGURATION

Similar to the optical crack detection according to the standardized test, the identification of the limiting configuration can be performed by analysis of the recorded video data. The axial view enables a unique identification of the first visible crack across the thickness. Fig. 2 shows by way of example the axial views of six sequentially recorded configurations. It can be clearly seen that in this case, initially local necking occurs followed by a crack across the thickness.

Alternatively, the limiting configuration can be identified on the basis of the $F$-$x$-curves, as the occurrence of macro-cracks is accompanied by a more or less pronounced variation of the punch force. Fig. 3 shows typical $F$-$x$-curves (types 1–4) as well as a reference curve, recorded on a specimen exhibiting an ideal hole edge. In case of $F$-$x$-curves exhibiting a pronounced drop, (Fig. 3, type 1) the limiting configuration can be identified by the maximum punch force. A sudden drop of the punch force correlates generally with the occurrence of the first through thickness crack.

If the recorded $F$-$x$-curves show a less pronounced variation of the punch force (Fig. 3, types 2, 3) it is advisable to determine the limiting configuration by assessment of the deviation of the curve from an appropriate reference curve. However, this requires additional hole expansion tests on specimens of the same material but of better hole edge quality.

The hypothesis employed for the identification of the limiting configuration from the $F$-$x$-curve can be verified with the help of the simultaneously recorded camera signal, especially to distinguish curves of type 3 and type 4 from each other.

#### 3.2 LIMITING HOLE EXPANSION RATIO

With the knowledge of the limiting configuration the evaluation of the recorded video data enables a direct quantification of the limiting hole diameter from the tilted, calibrated view. Neglecting effects of springback the limiting hole expansion ratio (in the following referred to as HER) can be directly determined. A correction of springback effects can also be considered to ensure comparability with experimental results according to the standardized test [1]. Likewise it is conceivable to estimate the HER directly on the basis of an $F$-$x$-curve. This requires a preceding systematic evaluation of the current hole diameters as a function of the punch displacement from the recorded video data (and/or numerical simulations), allowing a conversion of the punch displacement of the $F$-$x$-curve to current hole expansion and hence a direct evaluation of the HER. This method is promising for a fully automated test evaluation.

### 4 EXPERIMENTAL STUDY

The instrumented hole expansion set-up was applied to test sample series of two AHS steel grades, a dualphase steel (CR440Y780T-CP) and a complexphase steel (CR570Y780T-CP) of similar strength level, referred to as DP800 and CP800, s. Table 1. The holes were introduced either by punching (P) at a cutting clearance of 15% of the sheet thickness or by wire electrical discharge machining (W), respectively. In addition to the test geometry according to [1] (initial hole diameter $d_0 = 10\,\text{mm}$, cone angle $2\alpha = 60^\circ$) also different initial hole diameters (20, 25, 30 mm) and cone angles (20°, 40°) were considered, where for each parameter set 10 tests were carried out.

#### 4.1 RESULTS

The HERs of all specimens were determined on the basis of the recorded video signal, and are shown in dependence of the cone angle and the initial hole diameter in Figs. 4 and 5, respectively. The HERs of wire cut CP800 increase with decreasing initial hole diameter and with decreasing cone angle (except $d_0 = 10\,\text{mm}$, $2\alpha = 20^\circ$). In case of punched edges the HERs of CP800 also increase with decreasing initial hole diameter but decrease with decreasing cone angle. The HERs of DP800 (for wire cut and punched holes) are nearly independent of the cone angle and the initial hole diameter.

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1 Except for DP800 (W); here only two tests per parameter set.

The results are shown as trend lines in Figs. 4, 5 and 9.
Table 1: Tensile properties (tensile test in transverse direction; according to ISO6892)

<table>
<thead>
<tr>
<th>Steel grade (VDA239)</th>
<th>CR440Y780T-DP</th>
<th>CR570Y780T-CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel grade (EN 10136)</td>
<td>DC780X</td>
<td>DC780C</td>
</tr>
<tr>
<td>Thickness / mm</td>
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<td>1.36</td>
</tr>
<tr>
<td>Yield strength R_p0.2</td>
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<td>686</td>
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<tr>
<td>Ultimate tensile strength R_m</td>
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<td>Elongation at fracture %</td>
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<td>13</td>
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<tr>
<td>Strain hardening exponent n</td>
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<td>0.096</td>
</tr>
<tr>
<td>Vertical anisotropy r</td>
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<td>0.978</td>
</tr>
</tbody>
</table>

Some of the recorded F-x-curves are shown in Fig. 6. The scatter of the curves increases with decreasing cone angle and with decreasing initial hole diameter. In case of wire cut edges the F-x-curves are always of type 1, and the critical configurations determined via the maximum punch load or via the video signal are identical. The F-x-curves for punched holes and 60° cone angle are of type 2, in some cases of DP800 also of type 3. The maximum of the F-x-curve is reached significantly after the appearance of the first through thickness crack, wherefore the HER can be largely overestimated (5-10%) by evaluation according to the maximum punch force.

The F-x-curves of wire-cut specimens are in good agreement to the ones of punched specimens (until failure occurs) and therefore represent an appropriate reference curve to identify the critical configuration of the punched specimens by the deviation of their F-x-curves.

The range of spreading of the HER is considerably smaller (standard deviation < 3 %) for DP800 than for CP800 (standard deviation 5-10 %), where smaller scatter is observed in case of larger initial hole diameters.
However, CP800 at cone angles of 20° and 40° as well as punched hole edges also exhibits $F$-x-curves of type 4, where the evaluation of the HER has to be performed with considerable care. In case of wire-cut edges, expanded CP800 specimens show clear indications of plastic instabilities in a large region around the hole edge, s. Fig. 10, whereas in case of punched edges localized deformations can be observed only near the hole edge (s. Fig. 11). These localizations are more pronounced at larger initial hole diameters. In contrast, DP800 (in wire-cut and in punched condition) shows almost no indications of localized deformation and nearly no variation in sheet thickness along the hole edge (s. Figs. 11, 12).

Light optical micrographs of deformed specimens prove, that after a certain expansion, the near edge region of the specimen loses contact with the cone (s. Fig. 13). Hence, near the edge, no compressive stress in thickness direction is induced into the specimen resulting in a uniaxial stress state in circumferential direction at the hole edge.

4.2 DISCUSSION

In the hole expansion test the occurrence of plastic instabilities is shifted to higher plastic strains, wherefore at the uniaxially loaded hole edge much higher strains can be achieved than in tensile testing [2,3] or in tests used to determine forming limit curves (FLCs). The stabilizing effect is caused by the lesser strained material surrounding the hole edge [3] and can be described in a first approximation by the strain gradient at the hole edge in radial direction [7,8,10]. Assuming a simplified kinematics and neglecting local deformations due to hole preparation, the strain gradient can be estimated by the stabilizing parameter,

\[ \chi = -\frac{d\sigma}{d\varepsilon} \bigg|_{\varepsilon=0} = 2 \left( \frac{1 - \sin \alpha}{1 + \lambda} \right) \frac{d \varepsilon}{d \sigma} , \]  

(1)

with current hole expansion ratio $\lambda$, radial coordinate $s$ and plastic equivalent strain $\varepsilon$. The stabilizing parameter increases with decreasing cone angle, with decreasing initial hole diameter and with ongoing hole expansion [3].

To discuss the stabilizing effect on the forming limit, the relative gain in formability at the uniaxially loaded hole edge with respect to the limiting strain taken from the uniaxial stress path of the forming limit curve (FLC, s. Figs. 7,8), is correlated to the stabilizing parameter (s. Fig. 9). If failure is controlled by necking and not by local damage, this gain in formability can be further increased by increasing the stabilizing parameter, which is clearly the case for wire-cut CP800. This is supported by the fact that expanded CP800 specimens show clear evidence of necking controlled failure, which is most pronounced in case of large cone angles and large initial hole diameters (s. Fig. 10). At lower cone angles and smaller initial hole diameters these wave-like localizations are limited to gradually smaller areas around the hole edge, reflecting the increasing stabilizing effect.

Considering the same change of the strain gradient, the gain in formability is more sensitive to a variation of the cone angle than to a variation of the hole diameter (s. Fig. 9, CP800(W), $\alpha = 40°, 60°$). This results from the different impacts on the strain paths in the neighboring region of the hole edge. For smaller hole diameters, plain strain conditions move closer to the hole edge, whereas they move further apart for smaller cone angles, resulting in additional stabilization. The relevance of the strain in the neighboring region of the hole edge (in addition to the strain gradient) for the hole expansion behavior, at least in the necking controlled case, is also indicated by the appearance of plane strain necks at a certain distance from the hole edge at low cone angles (s. Fig. 10, top).

However, with further decreasing cone angle the gain in formability reaches a maximum and diminishes again (cf. Fig. 8, CP800(W) $\alpha = 20°$, $d_0 = 10\, \text{mm}$), as is also reported in literature in case of certain hole edge conditions [4,5]. The explanation for this phenomenon lies in the fact, that the local contact pressure between the hole edge of the specimen and expansion tool during the first stages of the test (configurations A-D in Fig. 3) is drastically rising with decreasing cone angle and decreasing hole diameter. This can be proved by simple mechanical considerations or numerical modelling, and is also confirmed by observations of the damage at the hole edges of expanded specimens via scanning electron microscopy (s. Fig. 14, top): A pattern of incipient cracks in radial direction is formed around the hole edge at the sheet surface, which is considerably more pronounced at smaller cone angles, thus accelerating the formation of through thickness cracks.

The sensitivity of this edge damage to the geometry of the expansion tool is even more pronounced for CP800 in punched condition (Fig. 14, bottom), which explains why smaller cone angles lead to decreasing formability (in spite of increasing stabilization) in this case (s. Figs. 4, 5, 9). Nevertheless, compared to the FLC, a considerable gain in formability is noticeable for CP800 in hole expansion testing, both in wire-cut and in punched condition – CP800 is not edge crack sensitive (s. Figs. 7,9).

In contrast, DP800 (both in wire-cut and punched condition) shows no significant influence of the stability parameter on the hole expansion behavior. Also the absence of necking prior to crack initiation, as well as the substantially lower spreading of the evaluated HERs compared with CP800, indicate damage-controlled failure. In punched condition, DP800 shows even a decrease of formability compared to the FLC level (s. Figs. 8,9) – hence this condition is edge crack sensitive.
Fig. 7 FLC versus HER, CP800.

Fig. 8 FLC versus HER, DP800.

Fig. 9 Relative increase in formability compared to FLC against stabilizing parameter, calculated in engineering strain (plot symbols according to Figs. 4 and 5).

Fig. 10 Plastic Instabilities.

Fig. 11 Deformation of punched edges, $2\alpha = 60^\circ$.

Fig. 12 Deformation of wire-cut edges, $2\alpha = 60^\circ$.

Fig. 13 Geometry of expanded specimens, CP800(P), ($d_0 = 10\text{mm}$), LOM.

Fig. 14 Damage of hole edges, ($d_0 = 20\text{mm}$), SEM.
5 CONCLUSIONS

Both the proposed, instrumented test setup and the evaluation strategies represent significant steps towards more (time and cost) efficient hole expansion testing. The recorded video data allow a complete evaluation similar to the standardized test. Direct comparability to test data according to [1] necessitates the correction of elastic springback and crack opening. However, it would be more reasonable to define the limiting hole expansion ratio without taking into account these effects, since the latter depend on specimen (component) geometry and hence do not represent characteristic material and/or edge-condition parameters. The recorded F-x-curves provide valuable information useful for both the verification of the evaluation of the video data and the analysis of damage/failure. In many cases, even a fully automated evaluation solely on the basis of F-x-curves seems to be feasible. The limiting configuration can be identified by the maximum punch force or the deviation relative to a reference curve obtained from tests on specimen with ideal edge conditions. The characteristics of the F-x-curve near the maximum punch force strongly depend on the edge-condition, the hole expansion geometry and the material behavior (strain hardening, damage evolution and fracture toughness). Whereas in case of wire-cut hole edges and low strain hardening the appearance of the first through thickness crack correlates to the maximum of the punch force, in case of punched edges and high strain hardening the first through thickness crack occurs considerably before the maximum punch force is reached. An efficient application of hole expansion tests also implies the exploitation of an understanding of possible damage and failure mechanisms to characterize the stretch-flangeability of a material at a minimum of experimental effort. In this respect tests employing different hole expansion geometries prove to be useful to determine failure governed by local damage or governed by necking. In case of damage-controlled failure, the limiting hole expansion ratio is nearly independent of the strain gradient and represents a characteristic material/edge-condition parameter describing stretch-flangeability and can be directly taken as limiting criterion in the numerical design of sheet metal forming operations. However, in case of necking-controlled failure, there is a strong dependence of the hole expansion behavior on the initial hole diameter and the cone angle. The limiting hole expansion ratio cannot be simply transferred to different hole expansion geometries and is therefore not suitable as criterion for the assessment of simulation data without taking into account the strain gradient [6]. As in any stability problem, imperfections (here: in-plane anisotropy, strain concentration along the sheared edge [7], etc.) may lead to a significant shift of the critical configuration to lower deformations and/or loads. In both cases, necking- and damage-controlled failure, in a comparison to the forming limit diagram a decision is to be made, which parameter is preferable to describe the limit of edge stretchability for the design of sheet forming operations [8,9]. However, the hole expansion test does not only examine the stretchability of cut edges, but also their sensitivity to the mechanical contact with the expansion tool, inducing additional local deformation and related damage. The contact conditions are strongly affected by the hole expansion geometry, where smaller initial hole diameters and smaller cone angles lead to significantly higher contact pressures and hence may lead to lower hole expansion ratios due to higher local damage at the hole edge (in spite of higher stabilizing effects). The consideration of these effects is an essential requirement of a reliable experimental assessment [11] and simulative description and of the stretch-flangeability and the edge crack sensitivity.

6 ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the Christian Doppler Research Association (CDG).

REFERENCES