THE RELATIONSHIP BETWEEN FORCE-EXTENSION DIAGRAM AND VISUAL INSPECTION ON THE EDGE CRACKING TENDENCY OF DUAL PHASE STEELS

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Abstract

Light-weighting targets of the automotive sector requires to use of advanced high-strength steels (AHSS) with higher strength more extensively. However, as a common behavior, increasing strength levels of AHSS accompanied with decreasing ductility/formability levels. This behavior become more pronounced during secondary deformation of a blanked edge. To examine this concept, hole expanding (HE) test, that simulates the local formability of the edges after blanking operations, has been started to be widely used. In this study, deformation stages of the HE tests were examined by means of main characteristics and variations of *F* (force) - *X* (extension) curves and derivative of *F* with respect to the X (*dF/dx*) during the punch travel until cracking. In order to correlate variation in curve characteristics with deformation stages, high-resolution camera images of the tested samples concurrently collected during the whole test and main relationships between them were determined. Based on these relationships a new approach to predict "stop stroke" of the HE tests is proposed. Therefore, elimination of the visual inspection and decision making of an operator or an in-situ image processing software is aimed. Proposed approach was developed using DP600 steel with a thickness of 1.2 mm as a common steel grade that widely used in automotive industry. Also, validation of developed "stop stroke" criteria was tried in HE testing of thinner and thicker DP600 samples. Results showed that a good prediction of stop stroke can be achieved by using proposed approach.

Keywords: Hole expansion, local formability, dual phase steels, edge cracking

1. INTRODUCTION

The ever-increasing expectation of low fuel consumption in modern automobiles requires reducing the body panel weights in the automotive sector. For weight reduction purposes materials with higher strength and adequate ductility have been started widely to be used by automotive industry. [1, 2]. Also, by aid of advanced stress analysis and optimization techniques, regions under effect of low stress levels are extracted via blanking or laser cutting techniques to increase weight reduction. In order to enhance strength of these extracted regions, one of the most widely used technique is forming of flanges at the edges [3, 4]. However, this approach also comes up with serious formability degradation problems due to increased cracking tendency of blanked edges [5]. The matter become more pronounced when this strength enhancement approach is applied to advanced high strength steels (AHSS) [6, 7]. This case requires to generate a local formability based input data for the design studies to form crack-free flanges in lightweight automobile body parts. Nevertheless, the traditional "Forming Limit Curve", which is widely used in simulation of the sheet metal forming operations, is insufficient to determine forming limits of an edge generated by blanking operations [8]. This is basically based on the fact that the process parameters used during blanking (punch / die clearance, cutting speed, etc.) cause significant changes in the mechanical behavior of the edges to be formed [8]. In this context, "Hole Expansion (HE) Test", which has been used to reveal local forming behaviors of blanked edges [2, 3, 6, 9, 10].

One of the important points in interpreting the results of the hole expansion test is the decision making for termination of the test. At present, according to ISO 16330 standard, an operator decides to terminate test by naked eye observation of a crack propagated through the full thickness. However, this human based decision-making procedure causes errors in repeatability of the test results. Consequently, it is necessary to perform this operation independent to human in order to enhance accuracy and repeatability of the HE test results.

On the point of view above, in this study, a new approach is proposed for decision making to terminate HE tests based on the punch force (*F*) and punch stroke (*X*) data. In order to build a determination criterion for HE tests, the relationships between the *F-X* curve characteristics and deformation behavior of a steel sheet using high definition camera images collected during the HE tests. In this criterion, it has been shown that, derivation of the punch force with respect to punch stroke can be used as a good, precise and low-cost indicator to determine the moment of crack initiation and propagation in the HE test.

2. MATERIAL METHOD

DP 600 steel sheets with chemical composition of 0.122 % C, 0.27 % Si,1.547 % Mn, 0.013 % P, 0.002 % S were chosen for study due to their wide range applications in automotive industry. The samples with the thickness of 1.2 mm were cut 100x100 mm. A hole with a 10 mm diameter was punched using a die with a clearance of 12.5 %.

Hole expansion test were performed on a servo-hydraulic test rig with a force capacity of 600 kN and instrumented with precise stroke sensors and high definition camera. The camera placed to the test rig with a sight direction coincident to punch axis as shown in **Figure 1(a)**. The tests were applied according to ISO 16630 using a 60° conical punch and 0.75 mm s^{-1} test speed without lubrication. Punch force (*F*) -punch stroke (*X*) data was collected during the test. In order to follow the deformation of the sample during the tests, an image processing software attached to camera was used. This software allows following the hole during the test and with this way the test can be stopped when the crack formation is seen on the video images. Based on ISO 16630, propagation of a crack through the thickness of the sample is considered as the termination condition. Hole expansion ratios (HER) were obtained for each sample as a percentage according to equation (1), where D_o and D_h are initial and final hole diameters, respectively.

Hole expansion ratio *(λ)* = $\frac{D_h - D_o}{D_0} * 100$ (1)

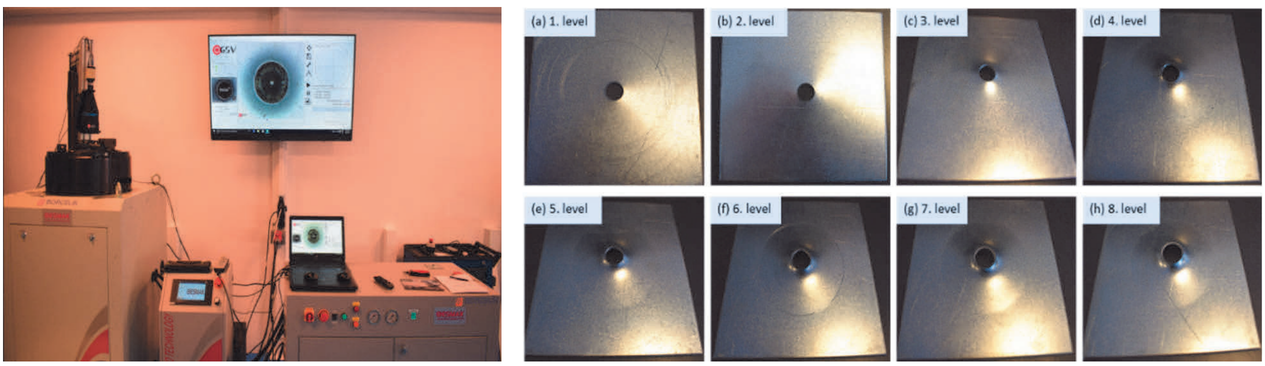
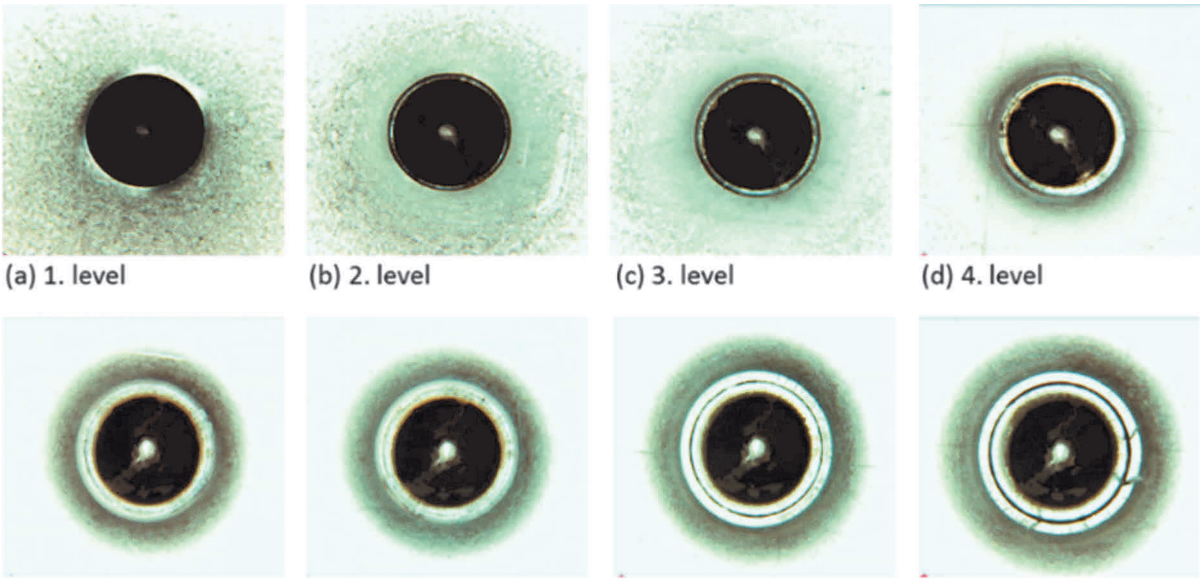


Figure 1 (a) Equipment for hole expansion test, (b) Photographs of tested samples

In order to follow the relationships between the deformation stages of the test and accompanied *F-X* characteristics early termination points were applied. In this direction, tests were stopped manually at different levels named as 1 to 8. The images of the expanded samples are shown in **Figure 2(b)**. On the purpose of observing the relationship between the camera images and the *F-X* curve and variation of first derivative of *F* with respect to *X* (*dF/dX*) were calculated and *X* versus *dF/dX* curves graphed. Each sample was cut with wire-EDM in the horizontal axis to measure thickness reduction of the expanded holes.

3. RESULTS and DISCUSSION

Punch strokes at termination, corresponding final diameters and HER% values of each deformation stage of HE tests of 1.2 mm thick DP600 steel is represented in **Table 1**. Photographs taken at the end of each deformation stages were represented in **Figure 2**. Stereo microscope views of cross-section of the samples tested with various punch strokes were represented in **Figure 3**. In these table and figures, levels 1-6 indicates conditions in which tests were terminated in punch strokes given in **Table 1** and level 8 represents the condition in which test was terminated using in-situ processing of live video images. Level 7 on the other hand, represents the condition in which the termination punch stroke was determined based on the approach that proposed in the current study to predict the punch stroke and/or level of deformation where cracks are expected to be initiated or about the propagate.



(a) 1. level (b) 2. level (c) 3. level (d) 4. level
(e) 5. level (f) 6. level (g) 7. level (h) 8. level

Figure 2 The hole images at the end of the test

As can be seen **Table 1** and **Figure 2**, increasing punch strokes caused a continuous increase in diameters of the holes. At the final level of the test 1.2 mm thick sample represented a HER of about 29.7 %. However, deformation of a sample did not occur in a homogenous manner by means of the punch stroke-hole diameter relationship. As can be seen in **Figure 2**, applied punch strokes expands the hole with a continuously variable contact between the conical surface of the punch and bottom edge of hole. According to ISO 16330 standard, initial holes of the HE tests were punched with a specified clearance leading to formation of three distinct regions through the thickness of the sample i.e: indentation zone, shear zone and fracture zone as shown in **Figure 3(a)**. Formation of these zones decreased the thickness of the hole from 1.2 mm to 1.145 mm after punching. At the initial levels of the deformation, conical punch surface mainly contacted with the indentation zone. This caused bottom hole edge to undergo local plastic deformation due to the nearly line contact (**Figure 3(b)**). As a result of this local contact condition, sheet thickness around the hole considerably decreased (**Figure 3(b)**). This local thinning also increased thinning per punch stroke (TPS) value (**Table 1**). Increasing the punch stroke affected the contact condition (**Figures 3c - 3d**) and transformed line contact type into area contact type. This transformation also sharply increased TPS as shown in **Table 1**. Area contact condition was also evident with increasing punch strokes but at the later levels of deformation, forming of the sheet by the conical punch, terminated the contract of the indentation edge to the punch (**Figures 3e - 3f**). This mainly caused a considerable decrease in thinning per punch stroke value (**Table 1**).

Table1 HER % values of the samples

Sample (level)	Diameter after expansion (mm)	HER (%)	Punch stroke (mm)	Hole thickness (μm)	Thinning per punch stroke (TPS) (μm/mm)
1	10	0	1.36	1135	7.35
2	10.09	0.9	2.43	1111	22.56
3	10.3	3	3.53	1056	50.00
5	11.17	11.7	5.97	1016	27.43
6	11.6	16	6.85	1014	2.27
7 (about to crack)	12.15	21.5	7.86	1006	7.92
8 (cracked)	12.97	29.7	9.03	1006	0

Above mentioned deformation stages/levels also alternate friction stresses, contact pressures thickness strains and strain rate through the test and thus, comprise a complicated deformation story. Moreover, pre-straining of the test samples during the punching operation forms a gradient of plastic deformation behavior, mechanical properties due to the strain hardening behavior and damage accumulation through the hole thickness. As one can expect, these variations are not easy to detect in a routine test. However, they may also be expected to be effective on variations of the punch forces with increasing punch stroke. Hence, punch force can be considered as a good indicator to plastic deformation history of the HE tests.

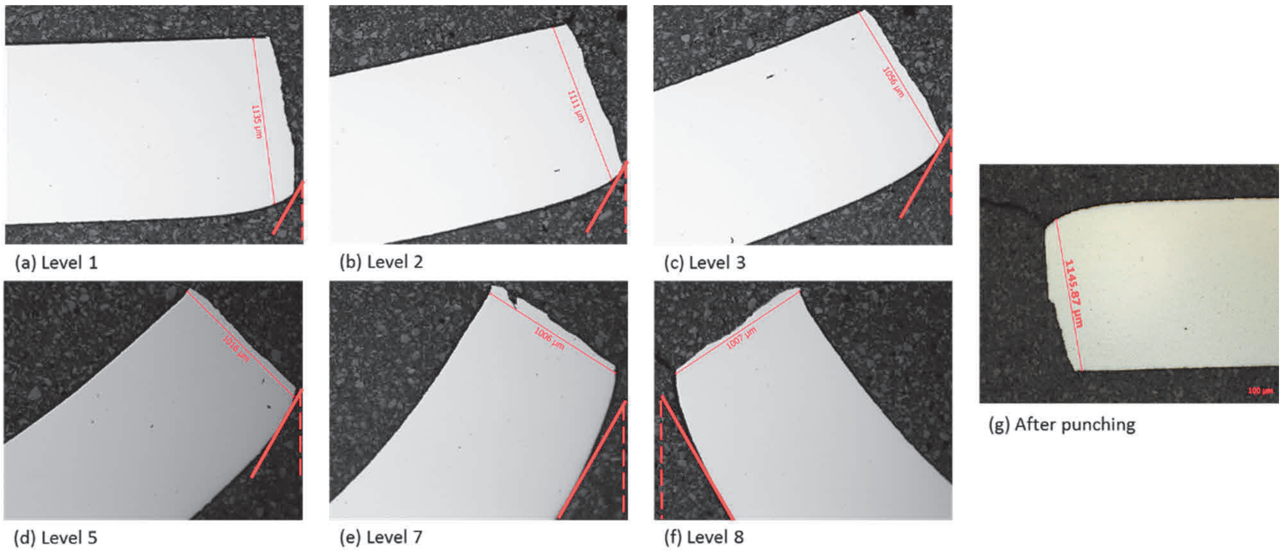


Figure 3 Cross-section thickness reduction measurement of samples

The *F-X* graphs of all levels obtained from the test results are as shown in **Figure 4**. When the basic characteristics of the *F-X* curves were examined, it is understood that all the deformation levels have the same tendencies and these curves are comparable to each other by means of deformation behavior. At the initial stages of the tests, a linear *F-X* relationship is evident. This may represent elastic bending of the sample at the beginning of the deformation. At the plastic deformation dominated levels of the HE tests *F-X* curve represented continuously increasing curve characteristics. However, increase in punch force values are strongly affected from corresponding deformation levels. In order to distinguish these deformation levels, *dF/dX* vs. *X* curves were represented in **Figure 5**.

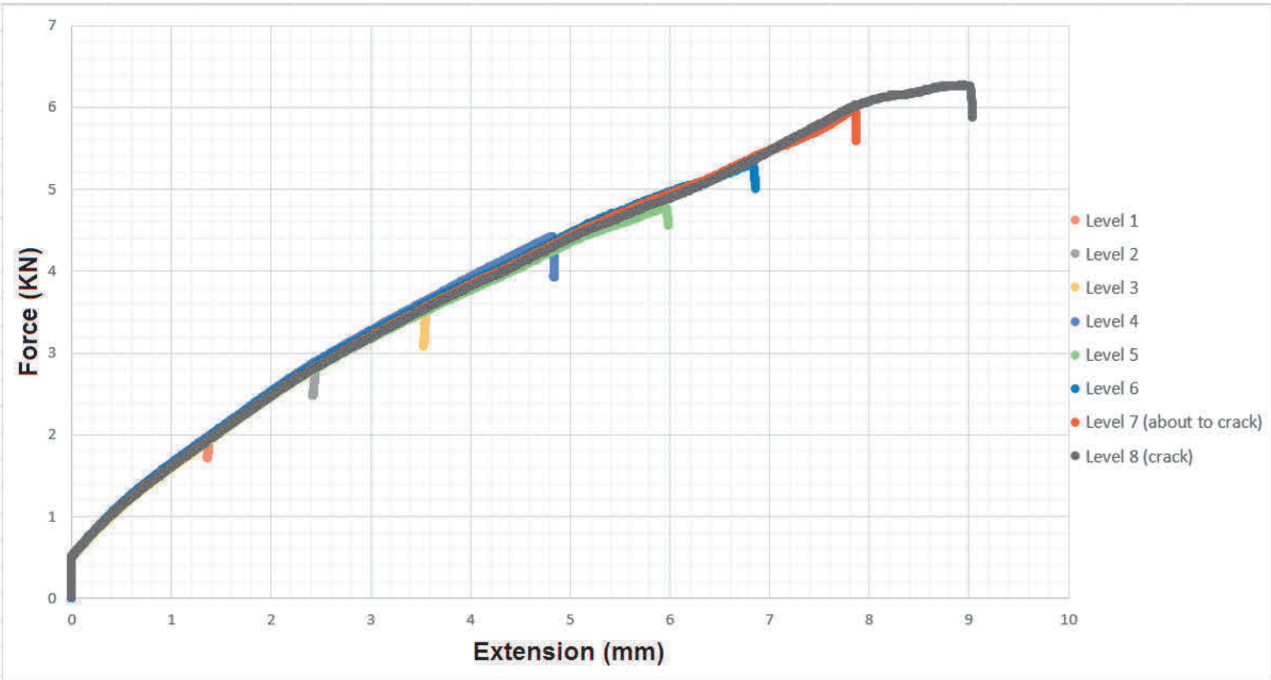


Figure 4 Punch stroke (*X*) vs. punch force (*F*) graphs of tested samples

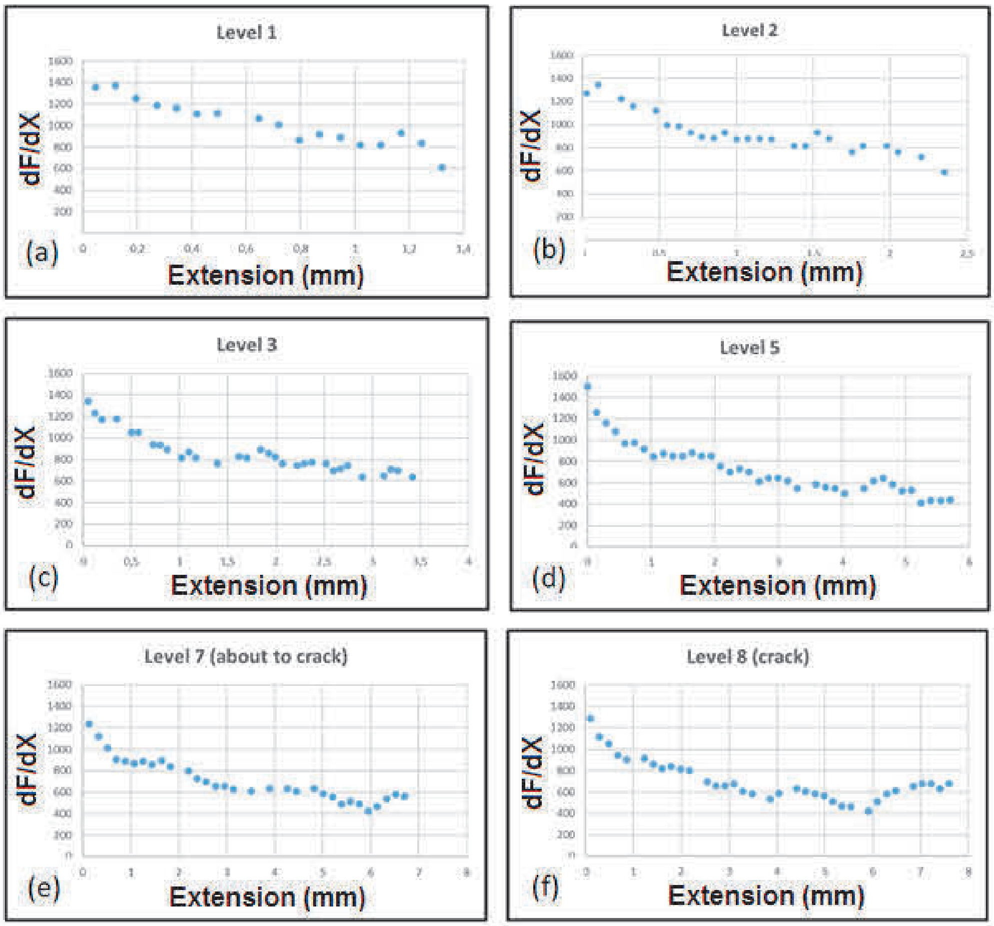


Figure 5 Alteration of *dF/dX* at the various levels of the HE tests

Figure 5 represents alteration of the *dF/dX* with punch displacement (*X*). At the initial stage of the deformation *dF/dX* remained constant through a limited punch displacement as a result of pure elastic bending of the sample (**Figure 5a**). Increasing punch displacement decreased *dF/dX* continuously (**Figures 5b-d**) and reached to a bottom value (**Figure 5d**). This value, represents the stage of deformation in which the contact between the indentation edge and conical surface of the punch terminated (**Figure 5d** and **Figure 3d**). Beyond this point *dF/dX* values increases sharply to the stage of where first crack is initiated (**Figure 5e** and **Figure 3e**). This condition can be clearly seen in **Figure 3e**. Also, an increase in TPS value at level 7 may be taken as a good indicator occurrence of necking leading to considerable thinning prior to crack initiation. *dF/dX* values remained neatly constant with further punch displacement (**Figure 5f**) at this stage of deformation cracks propagated through the thickness of the hole.

Based on above outlined experimental results, termination of the HE test can easily be predicted by observation of the *dF/dX* graphs. In order to validate proposed termination condition, 0.9 mm and 1.4 mm thick samples were also HE tested. Obtained *F-X* diagrams and *dF/dX-X* diagrams are represented in **Figure 6**. As can be understood from these diagrams, deformation stages in which crack initiation and propagation occurred can easily be predicted.

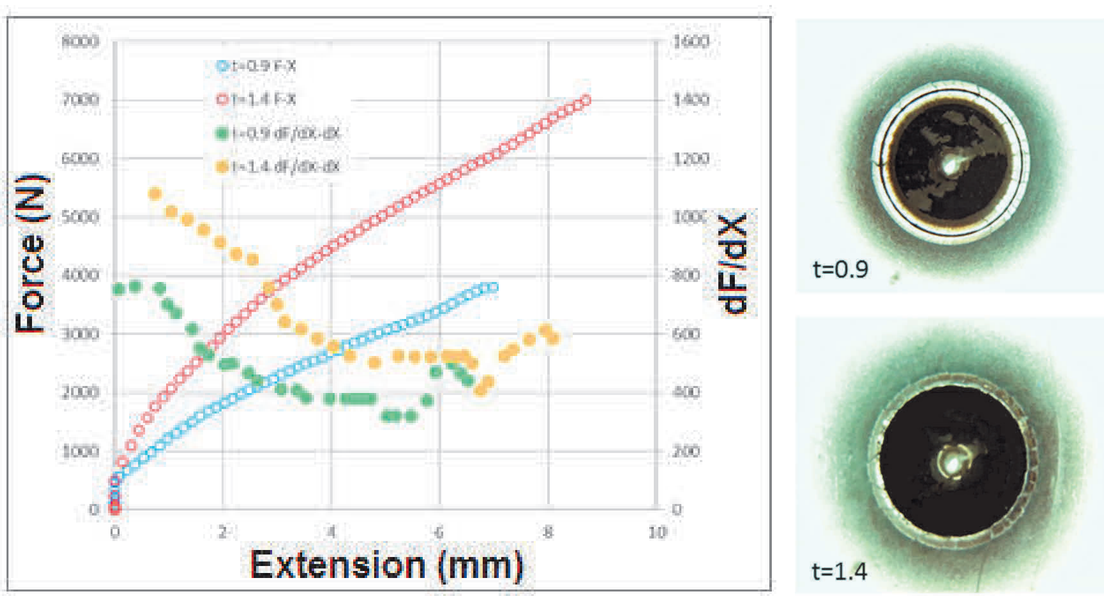


Figure 6 Results of 0.9 mm and 1.4 mm thicknesses

4. CONCLUSION

The main findings and conclusion of the study can be outlined as follows:

- Deformation of the sample does not occur in a homogenous manner by means of the punch stroke-hole diameter relationship in hole expanding test. This is mainly attributed to the variable contact conditions affecting friction stresses, contact pressures thickness strains and strain rate through the test.
- First derivative of punch force with respect to *X* (*dF/dX*) is a good indicator to deformation levels of the hole expanding tests. This parameter can be successfully used in determination of necking, crack initiation, crack propagation stages and termination point of the HE tests.

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