

# A Study of the Boundary Conditions in the ISO-16630 Hole Expansion Test

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**Abstract.** As new and more advanced sheet metal materials are introduced to the market, more accurate techniques for determination of failure limits are needed. One area that needs attention is edge formability, where the ISO-16630 standardized Hole Expansion Test currently is used to express this through the Hole Expansion Ratio. Over the years, this standard has been criticized for producing a large scatter in repeated tests. This paper investigates a new setup for the Hole Expansion Test which introduces draw beads into the setup to ensure sufficient restraining of the specimen during the test in an effort to reduced the scatter. In total 62 tests of a DP800 steel alloy were executed, but a large scatter in the results were still seen. It was therefore concluded that a lack of restraining force in the Hole Expansion Test was not the primary cause of the reported scatter seen in other tests.

## 1. Introduction

With the increased focus on combating the rising environmental issues in the world today, a key goal for most automotive manufacturers is to reduce the carbon-footprint of a vehicle throughout its lifetime. One way to do so is by introducing lightweight and eco-friendly materials into their products. These new materials are however much more advanced than their predecessors and therefore much more difficult to validate in the design and manufacturing feasibility analysis stages. One of the large challenges these new materials bring, is how to accurately predict edge fractures caused by straining of punched holes during the forming process.

In the past decade and more, the Hole Expansion Ratio (HER) has been used as a measure for the edge formability of materials. The HER value is determined through the ISO standardized Hole Expansion Test [1] where a conical punch is driven through a hole in the test specimen, with a diameter of 10 mm, until a through-thickness crack appears. The HER value is then determined as presented in Eq. 1, where  $D_h$  is the average hole diameter after rupture, and  $D_o$  is the original hole diameter.

$$\lambda = \frac{D_h - D_o}{D_o} \times 100 \quad (1)$$

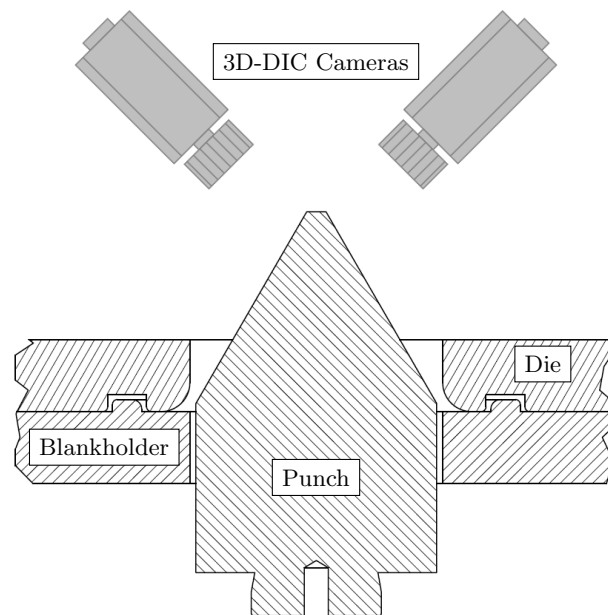
Over the years, the Hole Expansion Test has however been criticized by several authors, including Schneider et al. [2] and Larour et al. [3], for producing a high scatter when repeating the test on identical material from the same batch. Some authors, including Schneider et al. [2] and Chiriac & Chen [4], have attributed this to the operator reliant post-processing of the test,

however, this paper work with a different hypothesis: That the scatter is caused by insufficient restraining of the material during the test.

## 2. Experimental Setup and Specimen Preparation

In order to test if the restraining of the material during the Hole Expansion Test has an impact on the reported scatter, a new experimental setup was designed. In order to restrain the material, draw beads were introduced to the setup, where a die set from the Nakajima test setup, normally used to determine Forming Limit Curves, was used. With the application of an already existing die set for the Nakajima test setup, another benefit is also that the 3D Digital Image Correlation (DIC) system ARAMIS from GOM GmbH is embedded in the setup. According to Larour et al. [3] it should however be noted, that 3D DIC cannot be applied to materials where  $\lambda > 70\%$  since the cameras in the ARAMIS 3D DIC setup fails to focus once a punch displacement of 50 mm has been passed.

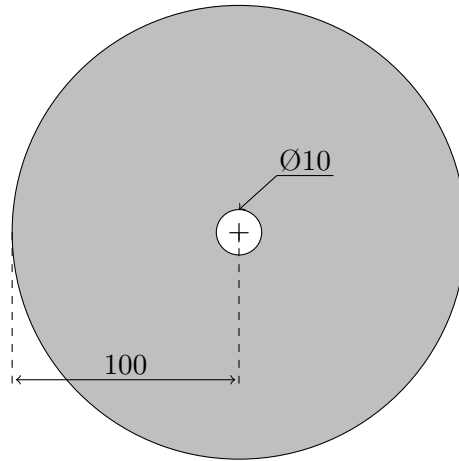
The main criteria to the punch according to the ISO standard is that the cone of the punch should have a tip angle of  $60.00 \pm 1^\circ$ . This criteria was taken into the design of the new punch, where the punch was scaled up to have a diameter of  $\text{Ø}100$  mm to fit in the Nakajima die. Another change that was implemented in the new punch is that the tip of the punch is cut away, so that the top of the punch is circular with a diameter of  $\text{Ø}8$  mm. This was done in order to provide the cameras for the 3D DIC with the most optimal conditions, and since the initial hole diameter of the test specimen is  $\text{Ø}10$  mm, this should have no influence on the test results. The new experimental design can be seen in Figure 1.



**Figure 1.** Cross-section view of the new experimental setup introducing draw beads and DIC system to the Hole Expansion Test.

Another change that was made from the ISO standard Hole Expansion Test is the shape of the blank. In the standard, the specimen is exemplified with a square blank, but in order to fit into the new setup with the die and blankholder from the Nakajima setup, the shape of the blank is changed to be circular. A requirement for the blank geometry is that "The test piece shall be flat and of such dimensions that the centre of any hole is not less than 45 mm from any edge of the test piece..." [1]. For this reason, the full-blank Nakajima geometry ( $\text{Ø}200$  mm) was

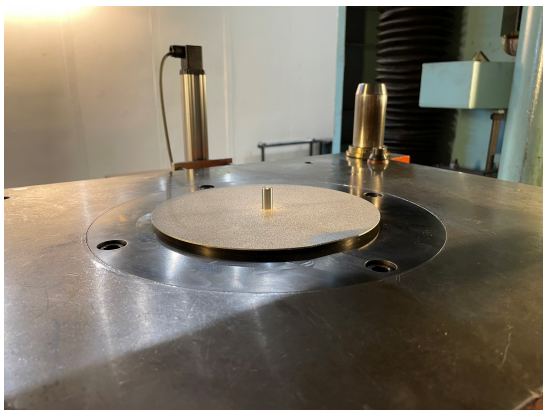
chosen, which ensures that the centre of the hole is 100 mm from the edge of the specimen. The geometry of the modified blank geometry can be seen in Figure 2.



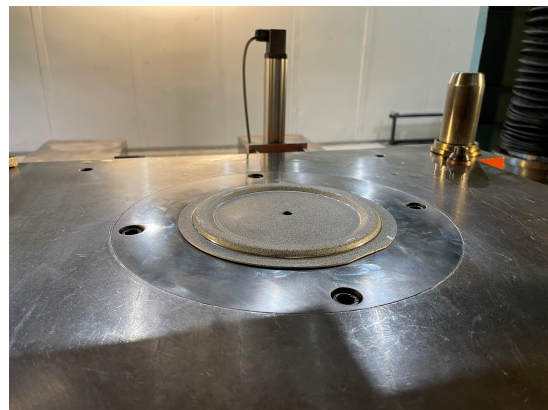
**Figure 2.** Modified blank geometry. All measurements in millimetres.

The cutting of the centre hole was performed using the punching operation, as specified in the ISO standard. This study focuses on a DP800 steel alloy with a sheet thickness of 1.2 mm, why a cutting clearance of  $12 \pm 1 \%$  was used as in agreement with the standard. This resulted in an inside diameter of the die of  $d_d = 10.288$  mm. Once the hole has been punched, a stochastic pattern is applied to the specimen to prepare it for DIC measurements. The pattern is applied so that the exit surface of the punched hole faces the die, thereby ensuring that the burrs created by the punching process faces away from the punch.

In order to ensure that the centre of the hole was aligned with the centre of the punch, a guide pin, mounted in a drilled hole on top of the punch, was used. The guide pin system can be seen in Figure 3 and a blank with formed draw bead can be seen in Figure 4.



**Figure 3.** Guide pin used for ensuring the centering of the hole.



**Figure 4.** Pre-formed blank after removal of guide pin and with draw beads formed.

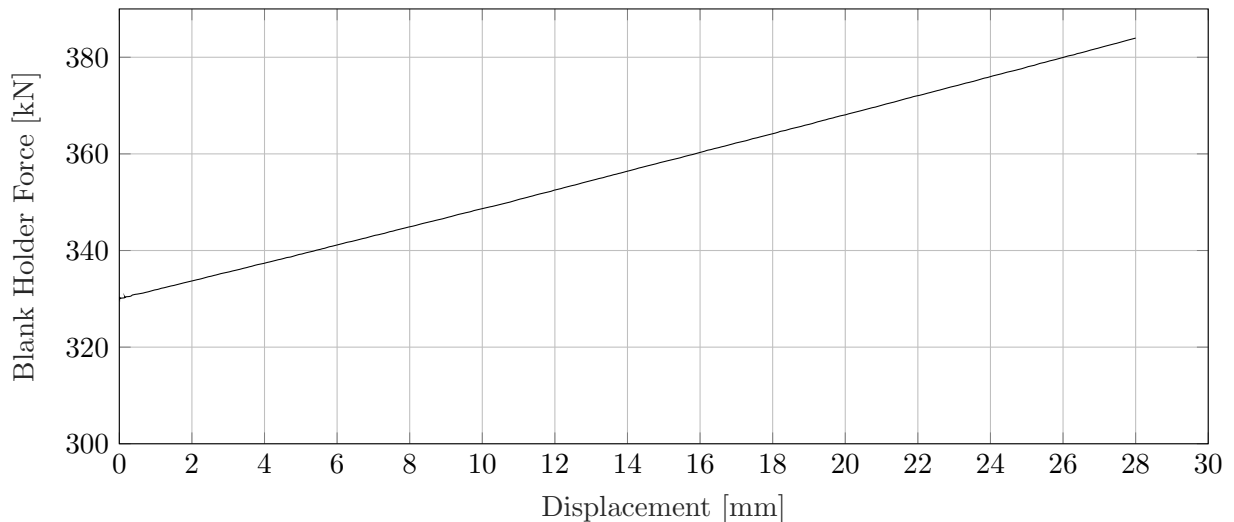
In order to form the draw bead, the rule of volume consistency dictates that the material used for this must be taken from somewhere else. Therefore, in order to ensure that the dimension of the centre hole was not changed radically during this "pre-forming" a test was conducted without the punch, so that only the draw bead was formed. A manual measurement of the

blank before the forming showed that the initial hole diameter was  $D_o = 10.013$  mm and the hole diameter after forming of the draw bead was  $D_h = 10.047$  mm. This results in an increase of the diameter of  $\lambda_{pre} = 0.34$  %, which is deemed negligible compared to the spread of the HER-values and to not influence the results of the Hole Expansion Test.

### 3. Experimental and Post-Processing Procedure

By moving the setup into a single-action Wemhöner hydraulic press with a press capacity of 1300 tons, another deviation from the ISO standard needs to be done. In the standard, a testing speed of 1 mm/s is specified, however, the minimum speed of the utilized press is 5 mm/s. Another challenge when moving to a hydraulic press is how to determine when a through-thickness crack has appeared. In the Nakajima test setup, the operator does not visually observe the crack, but detects it by listening, and once the crack is heard, the test is terminated. The edge cracks in the Hole Expansion Test are not possible to detect by listening for the particular material tested, why a certain point in time where the test should be terminated is difficult to determine. This causes a risk that too deep of a draw could damage the tooling. Therefore, a mechanical stop was implemented in the press ensuring a fixed depth of the drawing. Based on initial experiments, a maximum drawing depth of 28 mm was chosen.

Another factor, and an important one in this study, is the restraining force applied to the specimen. In the standard, the following is specified about the clamping force: *”Apply sufficiently high clamping force to the test piece to prevent any material draw-in from the clamping area during the test”*[1]. The term ‘a sufficiently high clamping force’ is open to interpretation, but an example is given in the standard stating that a clamping force of 50 kN or higher should be sufficient for a test piece with the dimension 150×150 mm. As this investigation focuses on a DP800 steel grade, the blank holder force used in the press was increased significantly to a starting force of 330 kN, and the force increases as the tests proceeds to more than 380 kN. This scenario is exemplified in Figure 5. With the combination of the draw bead and this level of blank holder force, it is believed that no draw-in will occur during the testing.

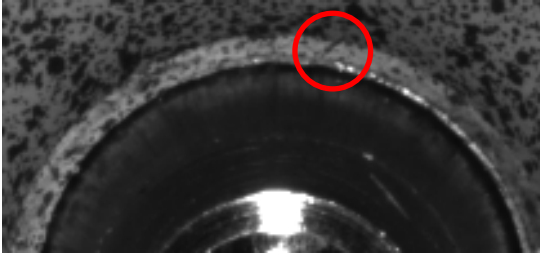


**Figure 5.** Blank holder force during one of the Hole Expansion Tests.

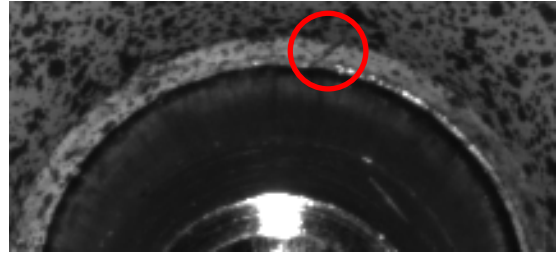
Fixing the draw depth is not without consequences. The obvious issue is that the final specimen will in the vast majority of the cases have passed a point where a through-thickness crack first appears. In the same way, cases where a through-thickness crack has yet not presented itself could occur. In the case of the latter, not much can be done in the setup, except changing

the mechanical stop, and try again. In the first case, the general methodology presented by Chiriac & Chen [4] can be utilized, where the Hole Expansion Test was recorded with a digital camera, and a digital measurement of the hole diameter occurs at the frame that shows the first through-thickness crack.

Therefore, by utilizing the images captured by the 3D DIC system (with a sampling frequency of 60 Hz), a measurement of the hole diameter of any given stage in the test is possible, and should result in a reduction of the uncertainties introduced by the operators reaction time. Figures 6 and 7 presents a close up of the collar on a Hole Expansion Test at two different stages with a draw depth difference of approximately 0.17 mm. In Figure 6 it can be seen that the crack has been initiated in the outer diameter, but has not yet propagated all the way through the thickness. Figure 7 presents the state of the collar two stages later, and here a full through thickness crack is present.



**Figure 6.** Close up of collar on test exhibiting crack initiation.



**Figure 7.** Close up of collar on test exhibiting through thickness crack.

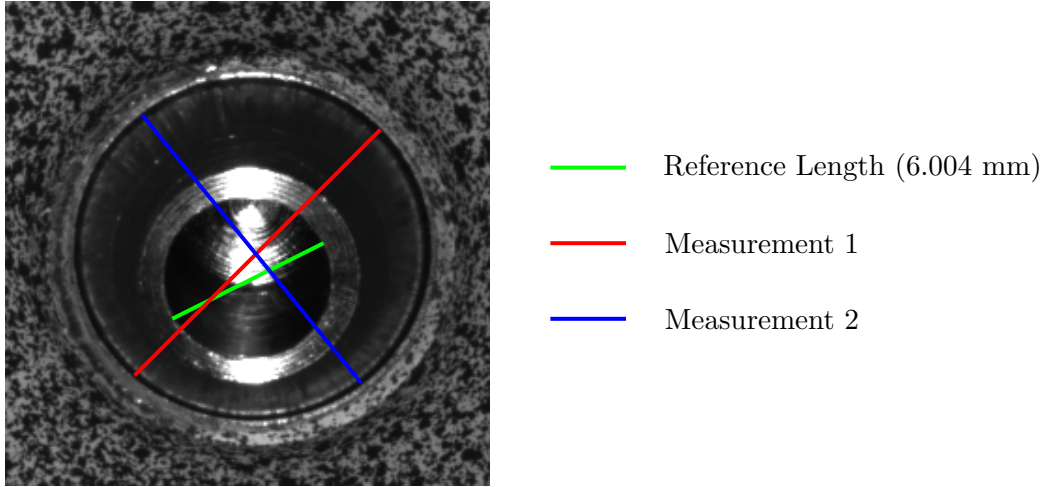
Once the stage where the initial through thickness crack appears had been identified, the diameter of the hole is measured based on a method mapping a certain number of pixels in the image to a reference length. In total, four measurements of the diameter were taken, two from the image of the left camera ( $D_{h1}$  and  $D_{h2}$ ) and two from the right camera ( $D_{h3}$  and  $D_{h4}$ ). The known reference length in the image is the hole made for mounting the guide pin presented in Figure 3, where the length is known to be 6.004 mm. Figure 8 presents where the reference geometry was taken, and how the two measurements are placed in relation to each other. Once the four measurements were obtained, the average Hole Expansion Ratio  $\bar{\lambda}$  was calculated using the average hole diameter  $\bar{D}_h$  as presented in Eq. 2.

$$\bar{\lambda} = \left( \frac{\left( \frac{D_{h1} + D_{h2} + D_{h3} + D_{h4}}{4} \right) - D_o}{D_o} \right) \times 100 \quad (2)$$

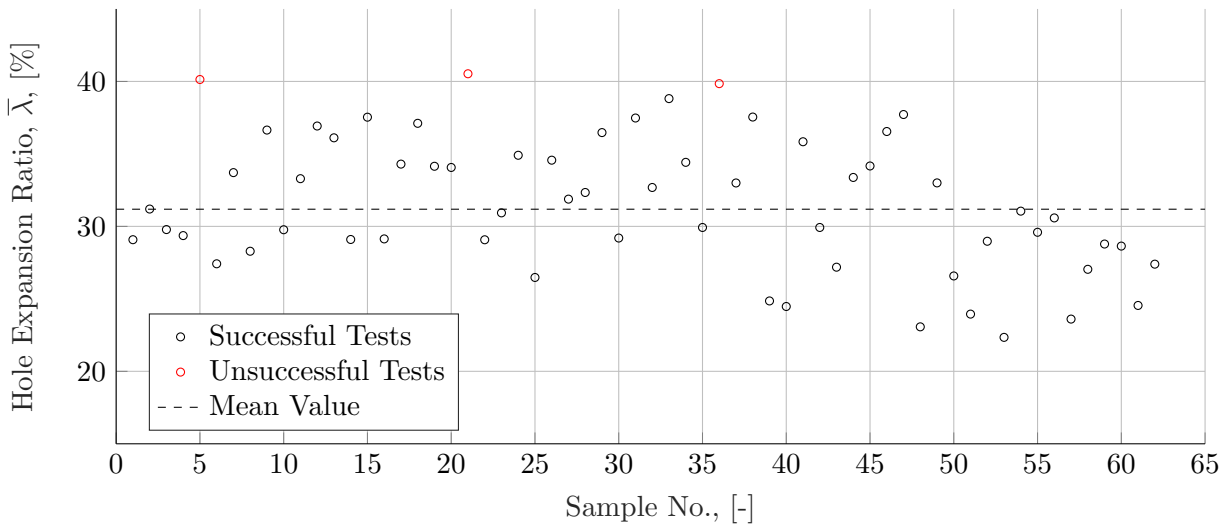
#### 4. Results

In total 62 test specimens were tested in the new experimental setup, where 59 of the executed tests were successful, and a through thickness crack was detected before the mechanical stop was reached. Three of the executed tests showed no evidence of fracture or only partial fracture (not through the thickness) at the point where the mechanical stop was reached. Figure 9 presents the  $\bar{\lambda}$ -values of the 62 tests, and the three unsuccessful tests have been marked separately. A mean value of the 59 successful tests was found to be 31.184 %, with a standard deviation of  $\sigma = 4.2910$ .

As it can be seen from the results presented in Figure 9, the test still produces a large scatter, indicating that the lack of restraining force in the test is not the primary cause of the reported scatter. An interesting trend that can be observed from the results, is the decrease of the  $\bar{\lambda}$ -values beginning with sample number 48. No apparent reason stands out when looking at the



**Figure 8.** Illustration of the measurement of the hole diameter. Two measurements are taken on each of the images recorded by the DIC system.



**Figure 9.** Hole Expansion Ratios of the 62 tests conducted. In total three tests were unsuccessful due to no presence of through-thickness cracks.

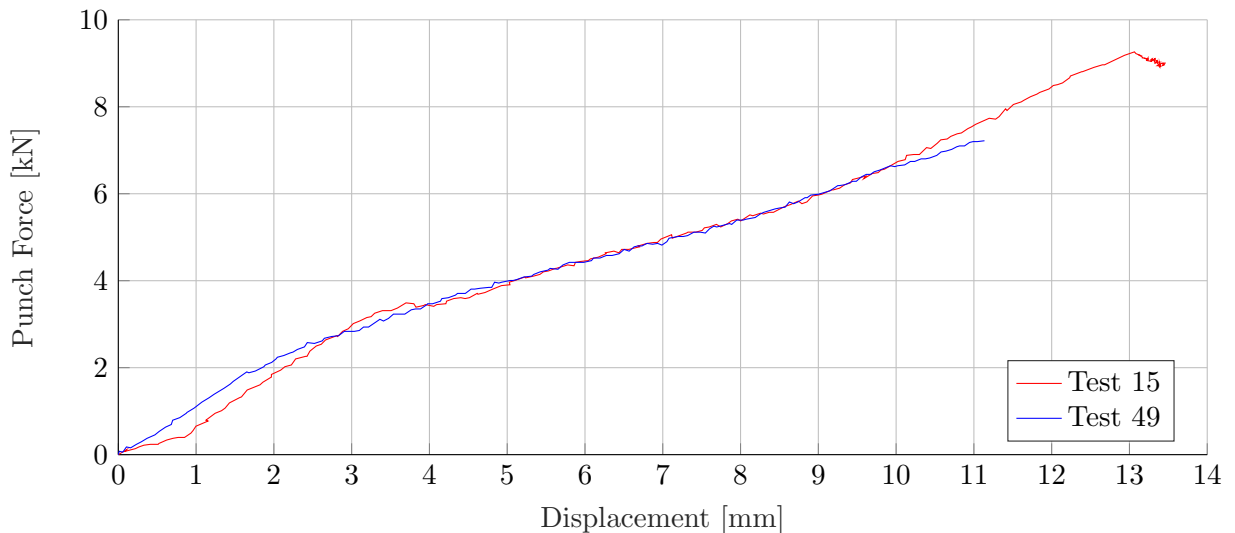
DIC stages at which the specimens failed, why a more in-depth discussion of the results must take place.

## 5. Discussion

As presented, the results of the 62 Hole Expansion Tests still produce a significant scatter, which indicates that the boundary conditions of the ISO-16630 test is not the primary cause for the scatter. Another factor that could highly influence the results of the test is the stochastic behaviour of fracture. Historically, the Hole Expansion Test has been evaluated once a through-thickness crack has appeared in the sample. With the previous setup this was the only way to proceed, but with the new setup presented in this paper, it is possible to evaluate the test in an arbitrary point in time due to the images recorded by the DIC system. Therefore, it could be

argued that the test should be evaluated at a stage before the first surface crack appears. The problem with edge cracks is that they are not induced by necking, but are subject to the direct fracture phenomena as described by Manopulo & Carleer [5]. Therefore, the current methods of determining the onset of localized necking as presented by e.g. Sigvant et al. [6] cannot be applied, and a different approach must be found.

Another interesting trend that was observed in the results is the downwards trend of the  $\bar{\lambda}$ -values on the last specimens tested (sample number 48-62). Several authors, including Yoon et al. [7] and Karelova et al. [8], have stressed the importance of the edge quality of the punched hole in the Hole Expansion Test. One possible explanation for the downwards trend in the results could be due to wear of the tool used for punching the holes in the test specimens. The tool used for punching in this series of experiments was new and never before used, why it is not unlikely what is seen is the tool experiencing some initial wear before settling into a stable condition. Another possible explanation for the trend could be an unintended wear of the conical punch. The scaled up punch used for the new setup was manufactured from a tool steel and subsequently vacuum hardened to have a hardness of  $61 \pm 1$  HRC. In order to get the punch to fit with the specifications, a grinding operation was performed after the hardening. If this grinding operation has removed most of the hardened material, it is possible that the conical punch has experienced some wear, which has resulted in a change in the friction conditions between the punch and the test specimen. Figure 10 presents a comparison of the Force-Displacement curves for test 15 and 49. This comparison shows that there are differences between the two curves, especially in the low displacement area, indicating that friction conditions might have changed between the punch and the sheet, as well as a difference in the total displacement accounting for the difference in the  $\bar{\lambda}$ -values of the two tests.



**Figure 10.** Comparison of the Force-Displacement response of two tests from each end of the test series.

## 6. Conclusion

A new experimental setup aiming to reduce scatter in the results of the ISO-16630 Hole Expansion Test was tested. The new setup was based on a hypothesis that the scatter reported by several authors was due to an insufficient restraining of the material during the test. Therefore, a conical punch was developed according to the specifications of the ISO-16630 standard and a

die set from a Nakajima test was used due to the presence of a draw bead. For the evaluation of the test, images from a 3D DIC system was analysed in a third party software where a mapping of pixels between a known distance and the hole diameter was used to determine the final hole diameter.

In total 62 tests of a DP800 steel alloy were performed, where 59 of these successfully presented a through-thickness crack, and the remaining three did not due to the test begin terminated by a mechanical stop in the hydraulic press used. The results of these 62 tests still presented a large scatter with a standard deviation of 4.291 % why it can be concluded that restraining force of the sample during the test is not the primary cause of the scatter in the Hole Expansion Test.

### Acknowledgements

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