IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

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To cite this article: A Leonhardt *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **480** 012026

IOP Conf. Series: Materials Science and Engineering 480 (2019) 012026 doi:10.1088/1757-899X/480/1/012026

Automated hole expansion test with pneumatic crack detection

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Abstract. The hole expansion test according to ISO 16630:2009 is a widely used method for determining the edge crack sensitivity, e. g. for advanced high strength steels (AHSS). However, the optical crack detection causes a subjective stop of the test, which is also difficult to automate. These existing disadvantages are eliminated by a newly developed method to stop the hole expansion test using pressure drop at an edge crack through the entire sheet thickness. The pneumatic crack detection ensures a high degree of objectivity and automation. The functionality of the new stopping method was experimentally proven by the comparison with the optical method, the investigation of the influence of different parameters and by testing of good part and reject batches from series production. The pneumatic method stops the test when through-thickness cracks are less pronounced up to a hole expansion ratio λ of approx. 35%, i. e. for materials sensitive to edge cracks. Thus, this variant provides more objective results than the optical method. The test results between the two methods are comparable in the range of $\lambda \leq 100\%$.

1. Introduction

Advanced high strength steels (AHSS) are increasingly being used in the automotive industry due to increasing efficiency and safety standards, but their formability is severely limited compared with that of conventional steels. They include dual-phase steels (DPS) which consist of a soft, ferritic matrix in which martensitic phases are embedded in an island shape to increase strength. A typical failure of these steels is edge cracking through sheet thickness, which is caused by forming of shear-cut component edges. However, new investigation methods are developed with great effort to determine the sensitivity to edge cracking since the failure due to edge cracking cannot be reliably predicted using conventional test methods such as the forming limit curve. **Table 1** summarizes a selection of the variants for determining the edge crack sensitivity for open and closed cutting lines described in literature.

Table 1. Testing procedures for determining the edge crack sensitivity.

Testing procedures for open cutting line	Testing procedures for closed cutting line
• Hole expansion test (ISO 16630) [1] • Collar forming test [2, 3] • KOBE tensile specimen with hole [2, 4]	• Tensile test with shear-cut edges [3] • NAKAZIMA tensile specimen / BMW edge cracking test [2, 3] • Half-specimen dome test [5] • DIABOLO test [6, 7] • Side bending test [8] • In-plane bending test [2, 7] • Double bending test [2] • Simulative flange test [9] • YOSHIDA test [2, 8]

The hole expansion test is a common procedure and standardized in ISO 16630:2009 [1]. A punched sheet sample is expanded by a conical punch until at least one crack runs through the entire sheet thickness. The hole expansion ratio λ (%) is then calculated as the characteristic value for the edge crack sensitivity using the following formula:

$$\lambda = \frac{D_h - D_0}{D_0} \cdot 100 \tag{1}$$

D_0 is the hole diameter before expanding, and D_h is the expanded diameter at the stop of the test.

A major problem of the hole expansion test lies in the distinct detection of a continuous crack, which is the stop criterion of the test. This point of time is currently determined by a metrologist and highly subjectively influenced. In addition, this optical crack detection method is difficult to automate. Various methods for crack detection have already been investigated in technical literature. These include, among others:

- Digital image correlation (DIC) [10, 11]
- Optical forming analysis [12]
- Active and passive thermography
- Detection of a defined force drop [10]

However, these solutions are very complex to implement, require cost-intensive measurement technology and can only be used to a limited extent. In addition, some methods react sensitively to external influences.

2. Hole expansion test with pneumatic crack detection

The development of a method for an automated procedure to determine the edge crack sensitivity of car body sheet materials eliminates the currently predominant subjective assessment of the inspector. The basic structure corresponds to the conventional hole expansion test in which the open die is replaced by a closed pressure cylinder (**Figure 1**). In the first stage, the conical punch is inserted into the hole of the clamped sheet until a seal is reached between punch and sheet. The pressure cylinder is then filled with compressed air to create an overpressure p_o. The hole is expanded using the punch in stage 3. As soon as a crack occurs that runs through the entire sheet thickness, the compressed air escapes to the outside and the pressure drops. This is detected with a manometer and used as a criterion for stopping the testing procedure.

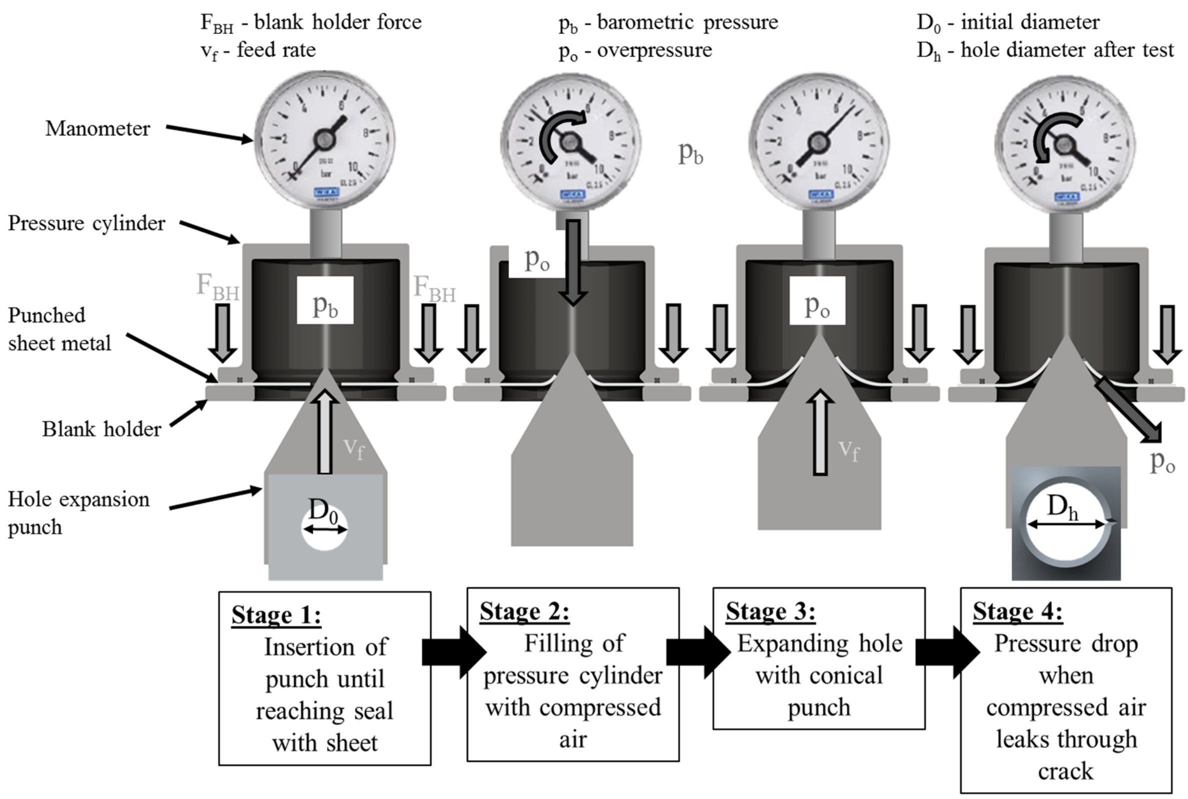

Figure 1. Schematic structure and sequence of the hole expansion test with pneumatic crack detection.

The method of pneumatic crack detection enables an objective stop of the test, which is independent of the tester. In addition, automation is possible as the pressure drop can be used as a control signal. Furthermore, the test can be implemented with simple and cost-effective tool and testing technology, and can be used on standard testing machines.

3. Experimental evidence of functional capability

3.1. Experimental plan and testing procedure

A comprehensive test program was carried out to validate the functionality of the hole expansion test with pneumatic crack detection (**Table 2**).

The tests were carried out on a servo spindle press, whereby the tool was used both for punching and for hole expansion with pneumatic crack detection. An initial pressure of 6 bar existed inside the pressure cylinder. The measurement of the pressure was executed by a pressure sensor. The hole expansion test was stopped as soon as a pressure drop of 0.03 bar occurred. The tests with optical crack detection were carried out by trained personnel from various steel manufacturers. The cold-formable dual-phase steel HC450XD was used for the majority of the tests as this material is particularly sensitive to edge cracking. The reason for this property is the structure of a soft, ferritic matrix in which hard martensite particles are embedded, and which contains the previous damage caused by shear cutting. Further investigated materials included an austenitic stainless steel, representing a possible alternative to dual-phase steel, and a 6000 aluminum alloy in outer skin quality. First, a comparison was made between the pneumatic and the optical crack detection. Scattering was determined in two test series, on the one hand by using an increased number of samples, and on the other hand with different materials having various hole expansion ratios. Furthermore, investigations were carried out regarding the influence of different parameters such as the hole insertion method, the cutting clearance and the pre-hole diameter, which influence the hole expansion capability. These investigations were performed in order to test the sensitivity of the new crack detection variant. In the end, batches of dual-phase steel were taken from series production, which led to reject components due to occurring edge cracks. These batches were also tested using the pneumatic stopping method in the hole expansion test. The maximum crack depths were also determined in addition to measuring the expanded diameters.

Table 2. Test program for the validation of the hole expansion test with pneumatic crack detection.

Name	Criterion	Material	Sheet thickness [mm]	Remarks	No.
A.1	**Comparison** of optical and pneumatic method	Dual-phase steel HC450XD	1.50	• Pneumatic method • Optical method by two steel manufacturers	15
A.2	**Comparison** of optical and pneumatic method	Dual-phase steel HC450XD	1.50	• Pneumatic method • Optical method by one steel manufacturer	5
		Dual-phase steel HC450XD	2.00		
		Austenitic stainless steel H500	1.50		
		6xxx aluminum EN AW-6016	1.04		
B.1	Influence of **hole insertion method**	Dual-phase steel HC450XD	1.50	• Shear cutting • Drilling • Drilling and reaming • Abrasive waterjet cutting • Laser cutting • Wire eroding	5
B.2	Influence of related **cutting clearance**	Dual-phase steel HC450XD	1.50	c_s = 6.67–33.33%	5
B.3	Influence of **initial hole diameter**	Dual-phase steel HC450XD	1.50	Ø = 6.65–22.00 mm	5
C	Investigation of **good and bad batches**	Dual-phase steel HC450XD	2.00	Different reasons for edge cracking in bad parts from series production	5

3.2. Results

Test series A.1 (**Figure 2a**) illustrates the subjective evaluation of a continuous crack when applying the optical method. On the one hand, this is demonstrated by the high fluctuations within a test series where the test is partly stopped too late. Thus the expansion of the hole is too high, the edge cracks are more pronounced and the maximum crack depths are larger. On the other hand, subjectivity is also reflected in the differences between the two results of the optical method to stop the test. Earlier stopping of the test can be detected for the highly edge crack-sensitive dual-phase steel by applying the pneumatic method so that the values for the hole expansion ratio are lower than those obtained by the optical method. Continuous edge cracks were found in all specimens, although they were less pronounced than the cracks determined with the optical method to stop the test. In addition, the fluctuations of the pneumatic method were the same or lower than those of the optical method. These results were confirmed in the second investigation comparing the two methods (A.2) for materials with a hole expansion ratio of up to approx. 35% (**Figure 2b**). However, it is evident that the cracks in the pneumatic variant were more pronounced and the maximum crack depths were larger with decreasing sensitivity to edge cracking and with increasing hole expansion ratio. The reason for this phenomenon is that the cracks must continue to grow until the pressure drop occurs as the material contacts the conical punch due to the higher expansion. Earlier or comparable stopping of the test can be detected with the pneumatic method up to a hole expansion ratio of approx. 100%. Above this value, the edge cracks are more likely to be detected with the optical variant.

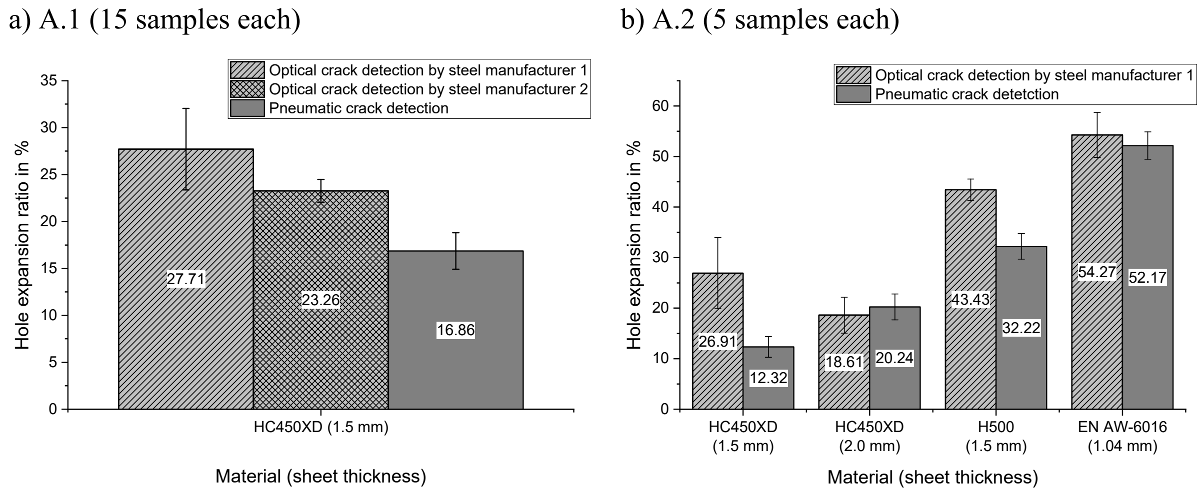

Figure 2. Comparison of hole expansion ratios during stop of the test, using optical and pneumatic method for a dual-phase steel sensitive to edge cracks (a) and for other car body materials (b).

The investigations of dual-phase steel with regard to the influence of various process parameters confirm the suitability of the hole expansion test with pneumatic crack detection (**Figure 3a-c**). **Figure 3a** shows the strong influence of the type of hole insertion (B.1) on the hole expansion ratio of HC450XD. The values for shear cutting are lowest since the cutting edge is pre-damaged by strain hardening and the occurring microcracks. This is particularly critical as this cutting method is generally used for high-volume sheet metal production. The hole expansion ratio can be increased by inserting the holes with a laser beam. Laser cutting is often used for tool and component testing in the early stages of product development processes. The higher hole expansion ratio must be taken into account since edge cracking can be caused by later application of shear cutting in series production. The other variants investigated for inserting the pre-hole also increase the expanded diameters, but are rather unsuitable for large series production. Shear cutting also shows a decrease in the hole expansion ratio with increasing cutting clearance in test series B.2 (**Figure 3b**). Only minor differences can be determined up to a related cutting clearance of 20.00%. This is followed by a sharp drop in the hole expansion ratio since a cutting clearance of 33.33% forms a large burr that is the starting point for crack initiation. Furthermore, an influence of the initial hole diameter (B.3) can be determined whereby the hole expansion ratio decreases with increasing diameter (**Figure 3c**). The number of continuous cracks along the circumference is higher for larger diameters, which means that more cracks cause a pressure drop. These cracks must therefore be less pronounced, but continuous, so that an earlier stop of the test occurs.

HC450XD with a sheet thickness of 2.0 mm was tested within a batch test (C) which is used for a component of the Volkswagen Group MQB platform. Three batches of the steel, which did not lead to reject production, provided the reference values. These expansion ratios were above 20% (**Figure 3d**). Furthermore, three batches were investigated in which edge cracks occurred in the outer edge of the component during the drawing stage, and one batch with edge cracks in the collar hole. These two failure types are typical for material batches with insufficient hole expansion capability. This was proven using the hole expansion test with pneumatic crack detection on the basis of the lower hole expansion ratios. A further batch with cracks in the flange was tested. This error, however, was caused by a forming tool that was not incorporated, leading to damage in the cutting edge in this area. As a result, the hole expansion ratio here lay above 20%, which was similar to the reference batches.

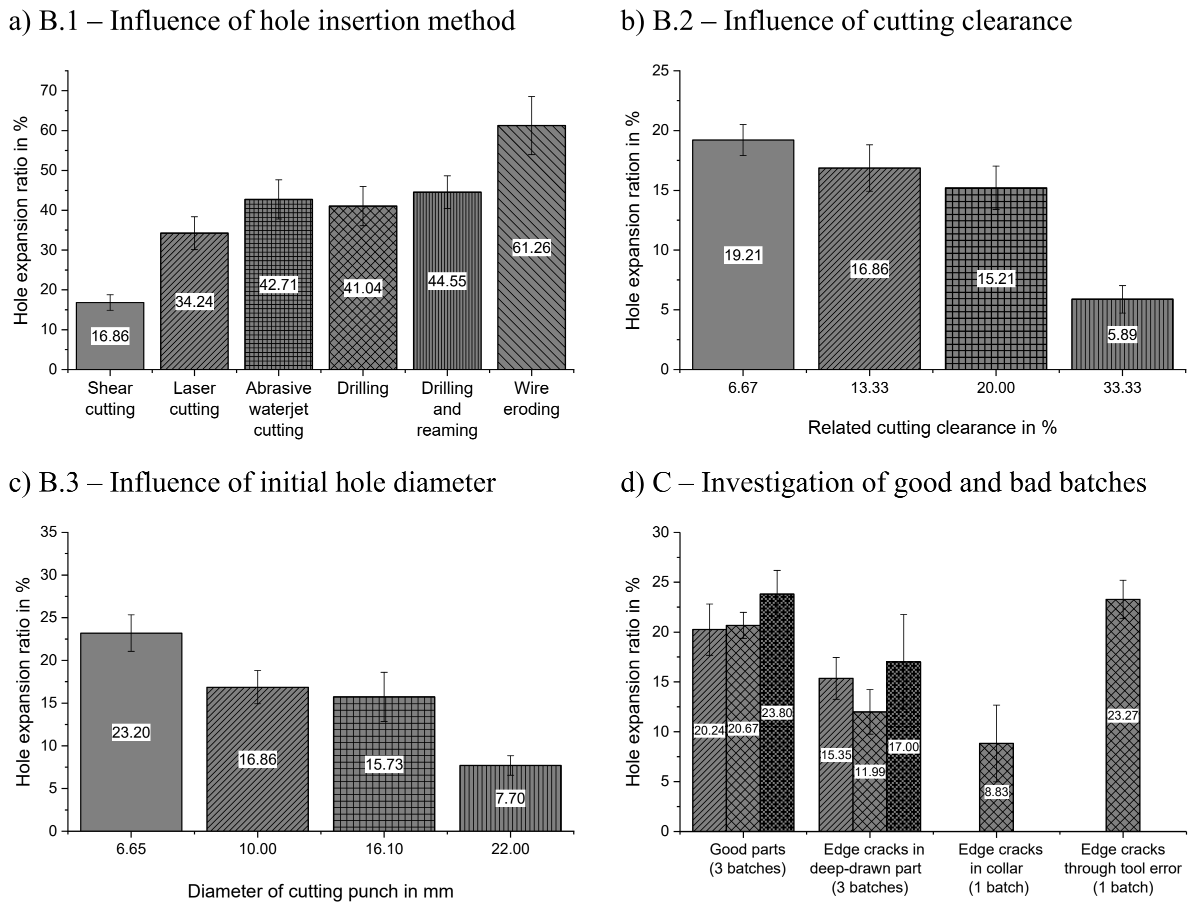

Figure 3. Investigation of the influence of various parameters on the hole expansion with pneumatic stop method for the dual-phase steel HC450 XD 1.5 mm (a-c), investigation of the edge crack sensitivity of good and bad batches of the dual-phase steel HC450XD 2.0 mm with pneumatic crack detection (d).

4. Conclusion and outlook

The hole expansion test for determining the sensitivity to edge cracking can be made more objective and automatable by using the introduced and investigated method of pneumatic crack detection. This method can be easily implemented. Compared to the optical method, it enables an earlier stop of the test as well as lower fluctuations for metallic car body materials up to a sheet thickness of 2.0 mm, which are highly sensitive to edge cracks ($\lambda < 35\%$). Using the pneumatic variant, better or comparable results can be achieved up to a hole expansion ratio of approx. 100% compared to the optical method for stopping the test. The optical method is to be preferred for values of λ above 100% due to the increase in crack formation for increasing hole expansion ratios since the crack depths required for the pressure drop are too large. The hole expansion test with pneumatic crack detection exhibits sufficient sensitivity to determine the influence of various process parameters and to identify material-related reject batches of a dual-phase steel. Subsequent research will deal with further validation of the pneumatic crack detection in other materials and by using other test centers. This will lead to further optimization and, if successful, standardization. The method will also be implemented in an experimental rig or in a universal testing machine. The application of the new testing method is conceivable for material users and material manufacturers for standard testing of selected material batches in the series process and for targeted optimization of new materials with regard to edge crack sensitivity. On the one hand, the characteristic value of the hole expansion can be implemented in the simulation model when designing new components. On the other hand, this test provides an opportunity to qualify pressed parts and tools more quickly, to carry out inspections of incoming material for quality control and to avoid rejects, and to clarify the causes of rejects by cross-checking the material in ongoing series production.

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