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Edge crack sensitivity of lightweight materials under different load conditions

I Tsoupis[1] and M Merklein[1]

[1] Institute of Manufacturing Technology, Department Mechanical Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Egerlandstraße 13, 91058 Erlangen, Germany

E-mail: ioannis.tsoupis@fau.de

Abstract. This study addresses the analysis of edge crack sensitivity of DP800 steel and AA5182 aluminum alloy in dependency of punching and machining operation as well as load case of subsequent forming. The inserting of a round hole by punching with defined punch-to-die-clearance, milling and drilling is compared. Subsequent forming is performed by standardized hole expansion test and by Nakajima-tests with three different specimen geometries. Local strain distribution at the surface for Nakajima-tests is measured by optical strain measurement technique and investigated in order to evaluate local deformation before failure. Additionally, resulting hole expansion ratio λ is determined. Significant higher λ as well as local strain values ε_{max} are achieved by machined holes. This is directly coupled to higher local formability and stretchability for both materials. Furthermore, the load condition has a strong impact on the edge crack sensitivity of the material. Prior failure is observed with changing stress conditions using different specimen geometries also influencing the reachable maximum failure strain. Higher edge crack sensitivity is observed for DP800, which is in good accordance to the material properties in terms of ductility and strength. These data in dependency of the process parameter can be used for the design of automotive components.

1. Introduction

Within the fabrication of automotive components multi-stage process sequences with punching and subsequent forming operations are commonly used. In this context holes in blanks are required for assembly in case of safety relevant structural components or as relief holes for deep drawing operations of body parts, for instance. According to economic reasons the holes are commonly punched in industry. This leads to a significant reduction of materials formability. More particularly, pre-punched areas have a negative effect on forming operations, which primarily occur during component production, concerning crack initiation. Especially, when modern lightweight materials are processed the formability of the sheared edges is restricted. First cracks occur in these regions as a result of work hardening and pre-damage. Consequently the quality of the hole is crucial to the arising damage intensity. Nowadays, the impact of shearing edge quality on subsequent forming is mainly assessed by the standardized hole expansion test [1]. However, the loading condition on the material and the strain evolution differs clearly to processes like deep drawing, as within the hole expansion test tangential tensile stresses and strains represent the dominant load leading to final failure [2]. Furthermore, higher local strains occur by hole expansion compared to uniaxial tensile loads [3]. Relating to material properties, the achievable hole expansions ratio λ, defined as the ratio of the initial and the resulting diameter of the hole, is generally higher with lower material strength [4] and higher

Lankford coefficient [5]. Also the type of cutting process [6], the punch-to-die clearance [7] as well as the position of the burr out of the shearing process and anisotropy of material [8] have a significant influence on the achievable hole expansion ratio and consequently, on edge crack sensitivity. Other investigations showed that test speed and clamping force of the blank holder have no significant influence on the hole expansion ratio [9]. However, the evaluation method by manual abortion of the test due to crack occurrence causes a high scatter in the results and is stated to be strongly subjective [10]. Additionally, other parameters like for example the tool affect the results [11]. First semi-automatic evaluation methods were published recently [12]. In consideration of the described aspects alternative approaches need to be developed [13] that can efficiently reflect the characteristics and influences of pre-punched blanks to subsequent forming processes [14]. In the scope of this work the formability of differently produced edges by punching and machining is analysed for various load cases for DP800 steel and AA5182 aluminum. A new evaluation method is presented in order to determine achievable hole expansion ratios and maximum strain levels.

2. Materials and methods

2.1. Materials

The materials used in this investigation are 5000 series aluminum alloy AA5182 as well as fine grained and cold rolled advanced high strength steel (AHSS) DP800, both with a sheet thickness of t_0 = 1.00 mm. These materials are typically used in automotive industry for structural components and body parts. Tensile tests at room temperature were carried out according to SEP 1240 with specimen geometry after DIN EN 10002-1 appendix B shape 2, in order to determine the mechanical properties of the steel sheets. The influence of the material orientation is taken into account by testing the specimen 0°, 45° and 90° to the rolling direction (RD). Figure 1 (a) shows representative true stress true strain curves of the materials and their extrapolation by analytical models, in particular by Hockett-Sherby in case of DP800 and a combination of Swift-Hockett-Sherby for AA5182. Independent of the rolling direction DP800 shows a stronger hardening in the beginning of the forming for strain levels $\varepsilon < 0.1$ compared to the aluminum alloy, whereas the hardening of AA5182 is constantly increasing. In sum this leads to higher hardening exponent for AA5182 ($n_A = 0.33$) than for DP800 ($n_S = 0.13$). The mechanical properties ultimate tensile strength and total elongation reveal an isotropic character of both materials as there are no significant differences in the strength values. The higher strength levels and lower ductility of DP800 steel have to be considered in the experimental analysis.

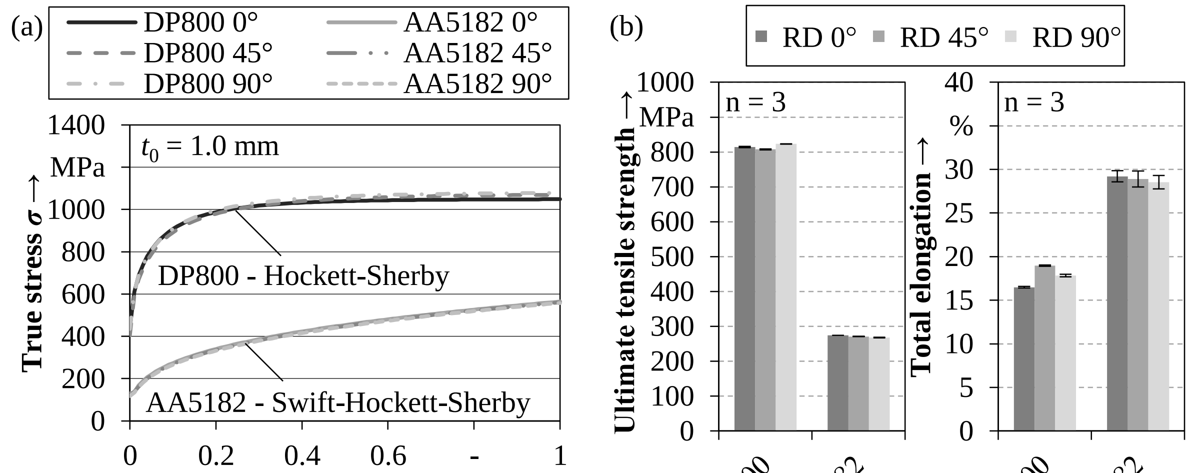

Figure 1. (a) Approximated and extrapolated true stress true strain curves
(b) Ultimate tensile strength and total elongation

2.2. Methods for the investigation of edge crack sensitivity

The edge crack sensitivity is evaluated by a combined analysis of achievable hole expansion ratios and the maximum strain levels in the regions of crack initiation. In order to respect different load conditions on the material, two test setups are incorporated within this work. On the one hand the hole expansion test according to ISO 16330 [1] with rectangular specimen is performed to study the stretchability of punched edges related to present industrial standards. On the other hand a stretch forming test in a modified Nakajima [15] test set up is used to stretch the hole in plane. Three geometries of specimen are tested to realize different strain and stress conditions. In particular, a full specimen (N-R0) and two notched specimen with different notch radii (N-R45 and N-R75) are used. The optical strain measurements system ARAMIS (GOM mbH, Braunschweig) is applied for both setups. This offers the advantage of investigating the deformation field at the outer surface of the specimen. Additionally, the system is used for determining the hole expansion ratio λ on basis of CCD-camera recorded pictures. In this context two of the main drawbacks of existing evaluation method can be overcome. By using the camera data the time of crack initiation can be exactly contained user independently and the measuring results are not influenced by springback effects of the material, which is the case by manual abortion criteria and following evaluation after unloading the specimen. Consequently, the hole expansion ratio is determined more accurately, reproducibly and practice-oriented.

The hole expansion ratio λ for the specimen of hole expansion test as well as for the Nakajima specimen is determined by the methodology shown in Figure *2* (a). Initial (D_0) and resulting (D_h) diameter of the hole are measured on basis of recorded pictures of the camera. By setting six pixel-points at the edge of the hole two isosceles triangles are defined, which are oriented perpendicular to each other to ensure an orthogonal measuring according to ISO 16330 [1]. By the points 1-3 and 4-6 two measure circuits are defined, which diameters are the basis for the calculation of the averaged diameter of the hole D_h. In relation to standard specification the occurrence of first crack through the sheet thickness is the criteria for measuring the resulting diameter D_h.

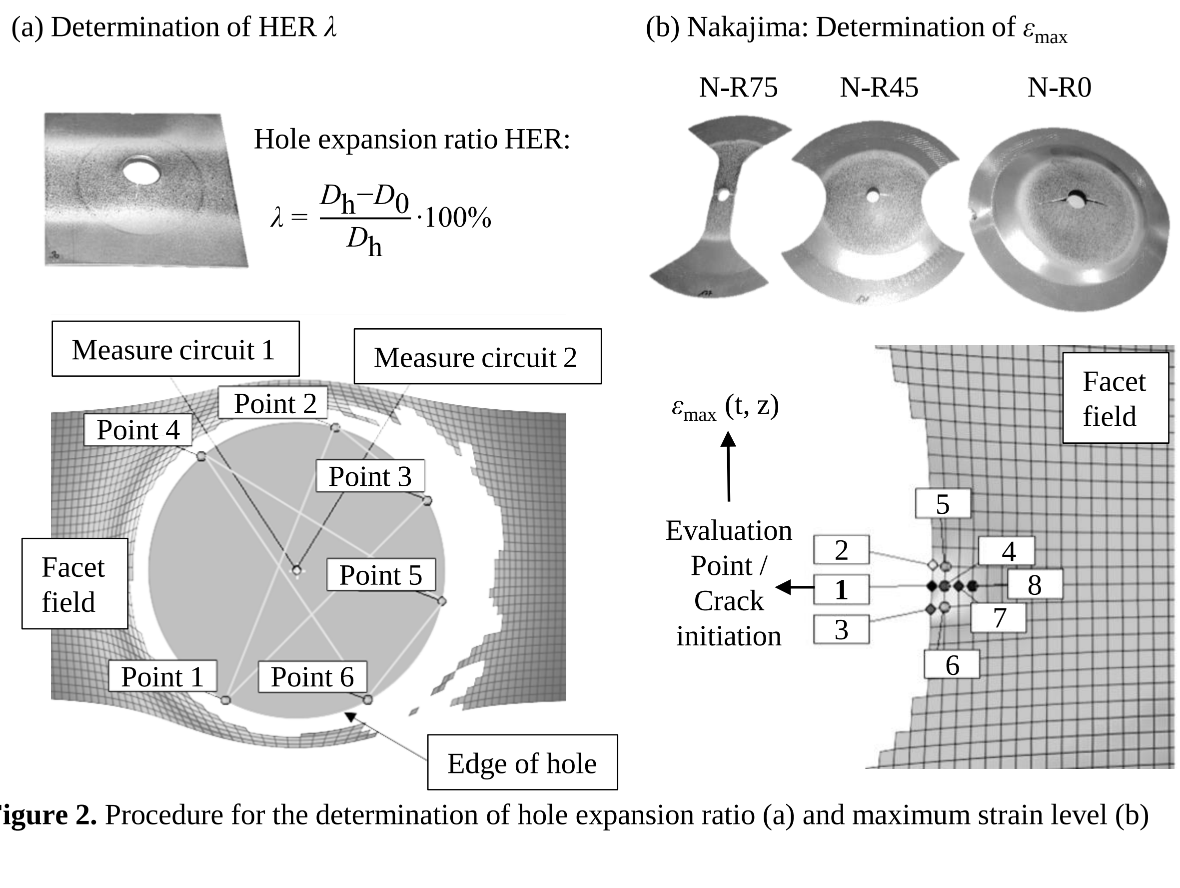

Figure 2. Procedure for the determination of hole expansion ratio (a) and maximum strain level (b)

The evaluation procedure for the Nakajima specimen N-R0 is analogue to the described one. As different load conditions for N-R45 and N-R75 conduct to increasing tensile stresses the hole is not stretched evenly. This leads to oval shaped holes with increasing notch radii. Thus, the determination of λ is based on the calculation of the major and minor diameter of the elliptical holes. This has to be considered by comparative evaluation of resulting hole expansion ratios.

The examination of the maximum strain levels for the Nakajima tests is carried out by the analysis of the deformation field at the outer surface of the specimen determined by ARAMIS system. The surrounding region of the crack is analysed by the strategy shown in Figure 2 (b). 8 measuring points in the facet field, where the crack initiates, are defined to capture the immediate surrounding within the deformation field. In this study point 1 is considered as it represents the maximum strain at the crack. The evolution of maximum strain value ε_{max} is analysed over the punch travel. The frame rate of image capturing is 10 Hz, the square and constant size of the facets is 0.25 mm x 0.25 mm. All experiments are evaluated until 0.1 s before first crack through the sheet thickness occurs. Consequently, the maximum strain evolution in critical regions can be opposed to each other comparatively for different specimen geometries and in dependency of the cutting process.

In order to investigate the influence of the cutting processes on the edge crack sensitivity three different industrial relevant processes are incorporated within this work. Considering machining as a process, milling and drilling are used to process a hole. In addition punching under a variation of the punch-to-die-clearance on two levels (c_1 = 0.10 mm, c_2 = 0.15 mm) is performed. In all processes the initial diameter of the hole is D_0 = 10 mm. Furthermore the influence of the punching process on the sheared edge is taken into account by varying the position of the burnish and consequently the fracture zone with regard to the punch in the subsequent forming process. On the one hand the fracture zone is located in the tensile stress dominated area averted to the punch (burr up) and on the other hand it is located facing the punch (burr down). Summarised, the parameters cutting process, punch-to-die-clearance c and the position of the burnish / fracture zone in case of punching, subsequent forming process and the material are varied and investigated in the next chapter.

3. Results

3.1. Hole expansion ratio

The hole expansion ratio λ determined by the described evaluation method is summarized in Figure 3 in dependency of the investigated parameters. Three valid tests are performed for the evaluation. The highest hole expansion ratios are reached in the hole expansion test, because the load condition is different to the Nakajima test. As within the hole expansion test a first flanging of the hole leads to further tangential stresses and strains, the hole is expanded in plane within the Nakjima test, which leads to more critical stresses directly at the edge of the hole. Also, significant higher hole expansion ratios for both materials are achievable by the cutting processes drilling and milling when HET and N-R0 are considered. The reason for this is the higher edge quality of the hole for these processes as there is no visible pre-damage and barely a hardening of the edge. For DP800 steel this is also the case for N-R45 and N-R75 as higher λ are measured for drilling and milling. The aluminum seems not to be that sensitive as there is no significant difference in the resulting hole expansion ratio. This can be explained by the high total elongation values of AA5182 in uniaxial tension. With increasing notch radii the predominant strain condition is more equal to uniaxial tension and thus failure is mainly caused by critical tensile stresses than by the edge condition. This is also an explanation for the small disparity of λ for this load cases regarding DP800. Comparing milling and drilling, higher values of λ are reached with milling in the HET, but vice versa in the N-R0. For the other Nakajima tests no significant difference can be identified, what makes it difficult to state an expressive conclusion.

However, concerning the process punching a trend to higher hole expansion ratios with increasing the punch-to-die-clearance from c_1 = 0.10 mm to c_2 = 0.15 mm is detected. This seems not to be logical as a measuring of the characteristic zones of the cutting edges shows, that higher punch-to-die-clearances lead to higher fracture zones and thus to higher pre-damage [16]. Conversely, further investigations by hardness measurements of the sheared edges reveal significant higher hardening of the edge within the smaller punch-to-die-clearance of c_1 = 0.10 mm. Consequently, the remaining formability for subsequent forming operation is reduced, which might be the more dominant factor within hole expansion when just considering the punch-to-die-clearance in the investigated range. Nevertheless, the hole expansion ratio is reduced, when changing the position of the fracture zone from down to up regarding the punch. In this context the influence of shear induced pre-damage becomes apparent. Within the fracture zone first cracks initiate due to higher roughness of the surface compared to the burnish zone, which can be seen in exemplary pictures of the sheared edge in Figure 3. Many small cracks occur circumferential the hole when fracture zone is located up. Again this trend is not that distinctive for the investigated aluminum confirming the higher sensitivity of dualphase steel on the formability of holed edges in sum. In comparison of both materials AA5182 shows higher hole expansion rations for all analysed parameter combinations by trend. This can be lead back to the higher ductility and lower strength values compared to DP800. A more sophisticated analysis of occurring strains and reachable punch stroke seems to be constructive to understand the present findings more in detail.

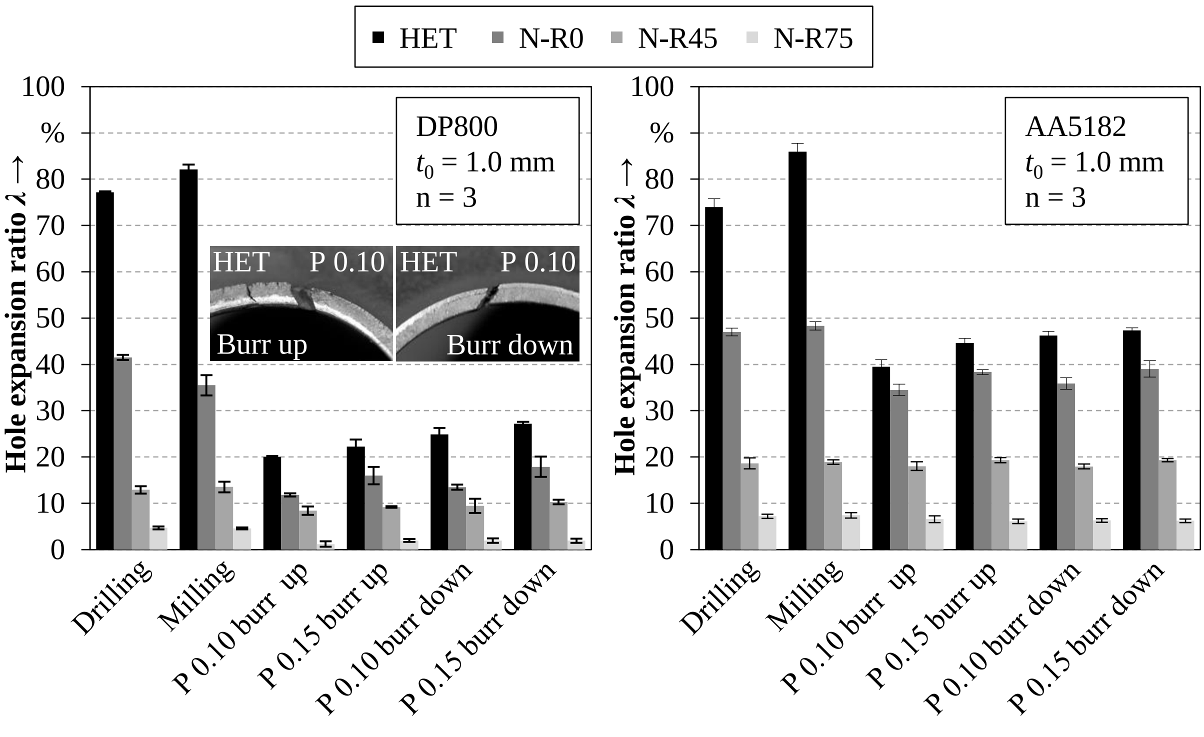

Figure 3. Hole expansion ratios for DP800 and AA5182 material

3.2. Evolution of maximum major strain

The evolution of the maximum major strain ε_{max} according to the presented evaluation method for Nakajima test specimens is summarized in Figure 4 for DP800 steel and in Figure 5 for AA5182 aluminum. For every parameter combination one representative curve is shown out of three experiments. The contact of punch and blank starts after a punch travel of 5 mm. After another 5 mm the maximum major strain starts to increase with ongoing plastification of the material. The slope of the curve is strongly dependent on the considered geometry of the specimen and thus on the stress and strain condition. With increasing notch radii also the slope of the curve is increasing independently of the material. Considering drilling and milling higher values of maximum major strain ε_{max} in comparable levels of $0.5 < \varepsilon_{max} < 0.55$ are reached for all specimen geometries in case of DP800 steel. However, maximum punch travel differs widely, which is in direct relation with the achievable hole expansion ratio λ. The main reason for the deviation is the obtained stress conditions on the material within the specimen geometries. For increasing notch radii the stress condition at the hole changes

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starting from stretching within N-R0 to more critical conditions. From N-R45 to N-R75 the percentage of uniaxial tension and stress state is raising leading to prior failure. Simultaneously, the mentioned fact that maximum strain levels are equal shows that sustainable strains of the material seem to have a major influence on the failure behaviour, which is directly dependent on the load condition.

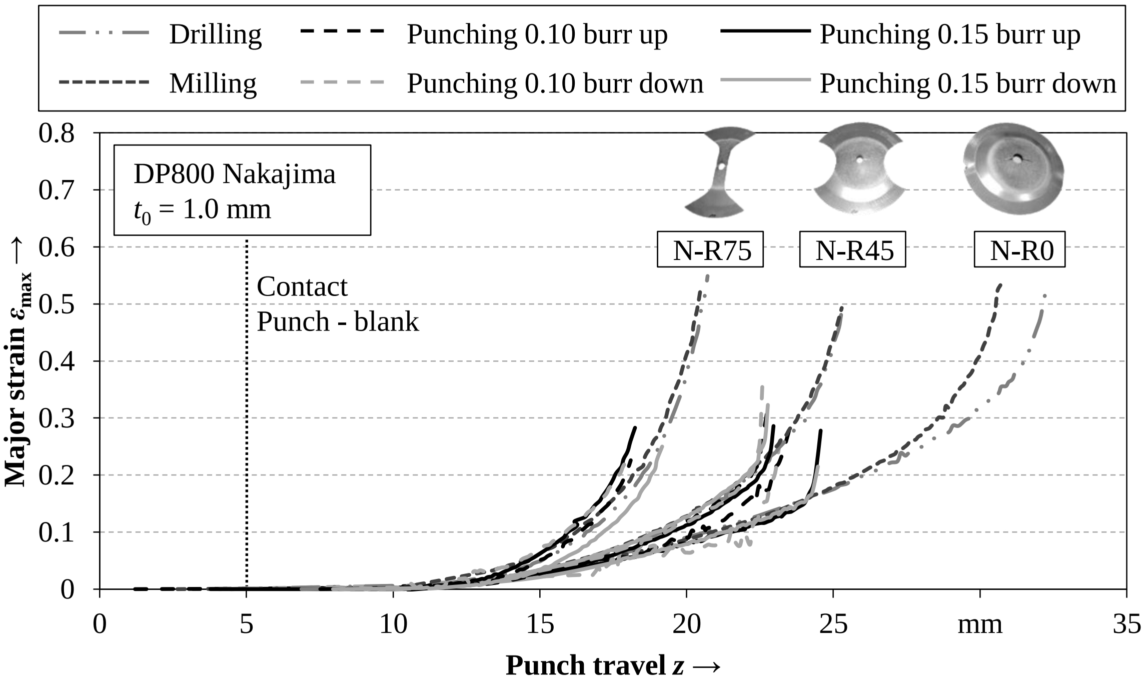

Figure 4. Evolution of the maximum major strain for DP800 material

In case of punching a significant reduction for both the punch stroke and the maximum major strain is recognizable. In this context the slightly better formability of punched edges with c_2 = 0.15 mm for N-R0 becomes clear as the punch travel is higher than for c_1 = 0.10 mm, what is consistent with the results of HET. This trend is also visible for the other specimen geometries, even though not that distinctive, because critical tension load is the dominant factor for failure as discussed before. Summarized, punching-induced pre-damage clearly affects the formability of the edge and decreases significantly the strain to failure for DP800.

In general, the results concerning milling and drilling are transferable to AA5182 aluminum. In contrast to the investigated steel the influence of specimen geometry is more pronounced respecting obtained maximum strain values. Strain is more concentrated for notched specimen due to resulting load condition and within the aluminum alloy the higher hardening exponent leads to higher strains. However, the influence of cutting process on the reachable strains is not as significant as for the DP800 steel. The strain-stroke-curves follow a similar trend for the considered specimen geometries, see Figure 5. The strong increase of the strains in the end of forming before fracture is a direct result of beginning necking, which simultaneously initiates shear fracture. As for N-R0 stretching of the hole is the load case the deformation of the material is distributed more evenly over a larger area leading to better formability and also higher hole expansion ratios. Apart from that sustainable strains before fracture are lower compared to the other geometries. Another effect that can be seen in the curves for AA5182, especially for the ones of N-R0, is the stepwise run of the curve resulting in a rapid slope in the end. This can be lead back to the Portevin-Le Chatelier effect, which is a result of dynamic strain aging or related to plastic strain inhomogeneity in solid solutions [17]. The effect is rated not to have a significant influence on the resulting formability itself and consequently is not considered within this work.

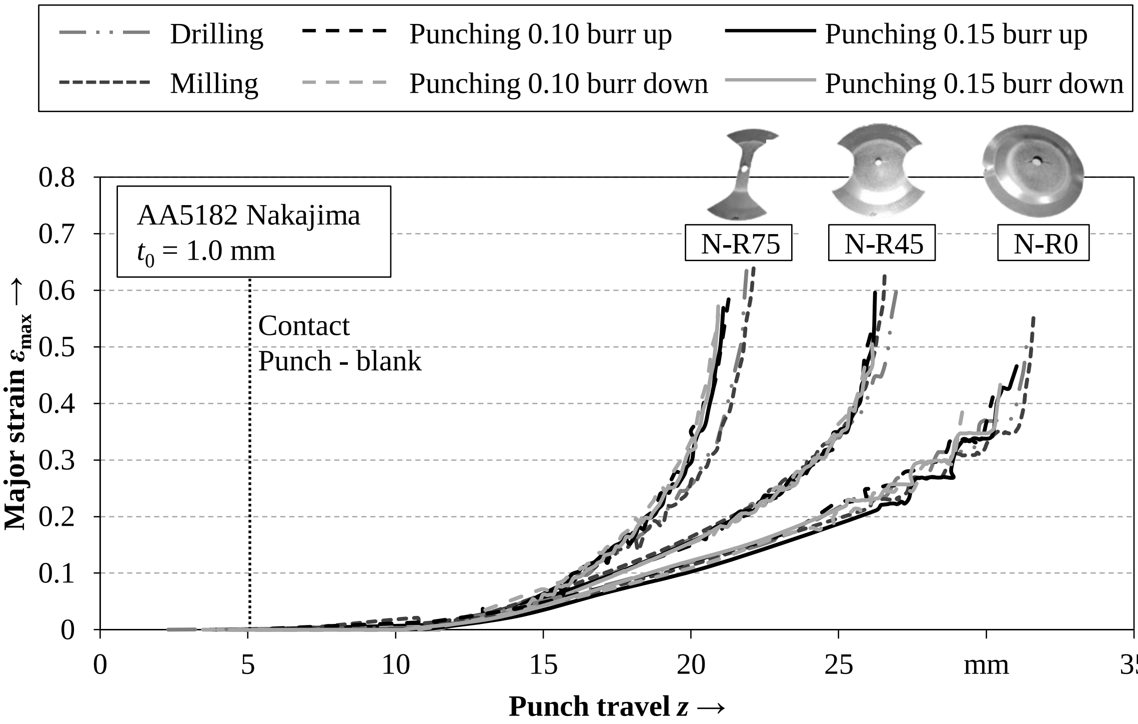

Figure 5. Evolution of the maximum major strain for AA5182 material

Comparing these results with the ones from the hole expansion test, no direct correlation can be seen. Based on the results of the hole expansion test the significant influence of the cutting process and the loading condition is more distinctive in the absolute value λ. However, no information on sustainable strains of the material and the formability around the edge can be provided by HET. This leads to the conclusion that a combined investigation using the presented methods to determine the hole expansion ratio and maximum major strain is necessary to evaluate the formability concerning the edge crack sensitivity in dependency of the considered parameters.

4. Conclusion and outlook

Within this research the edge crack sensitivity of AHSS steel DP800 and aluminum alloy AA5182 is investigated in dependency of the cutting processes milling, drilling and punching as well as the subsequent forming process. A novel evaluation method based on an optical measurement system is presented in order to determine the hole expansion ratio and the maximum strain levels at the region of crack occurrence. Edge crack sensitivity is significantly affected by the cutting process. Machining processes drilling and milling provide comparable results concerning the hole expansion ratio and the reachable maximum stain levels in dependency of the load condition and the material. Edges produced by these processes are more stable against crack sensitivity. Punching affects the formability of the edges significantly as the hole expansion ratio is reduced for both materials. However, the sensitivity is more pronounced for DP800 steel, which in sum also shows lower formability of the edge due to higher strength and lower ductility in comparison to AA5182. In case of punching the position of the fracture zone up within subsequent forming decreases the formability according to induced pre-damage and rougher surface in this zone. Also a decrease of the punch-to-die-clearance from 0.15 mm to 0.10 mm reduces the edge formability due to greater hardening of the material in the region of the edge. The results can be used in the design process or for the deduction of characteristic values in the numerical simulation for the estimation of the edge crack sensitivity in dependency of the investigated parameters. In further investigations the influence of material microstructure is investigated as the current results do not give information on the damage and failure modes in particular. Additionally, a study of the deformation field around the crack seems to be promising to understand these mechanisms more in detail.

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