Materials Research Proceedings **25** (2023) 329-336 https://doi.org/10.21741/9781644902417-41

Numerical analyses of the influence of a counter punch during deep drawing

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Keywords: Fracture Analysis, High Strength Steel, Process Extension

Abstract. In the automotive sector, the demand for high crash safety and lightweight construction has led to an increased use of steels with higher strengths. However, the rising number of varying materials with different strengths and ductilities lead to an increasing complexity in production, making it more challenging to ensure robust processes. Therefore, the focus of current researches still lays on the further development and extension of forming processes to enable high productivity and reliable production. A powerful tool for an efficient optimisation and extension of forming processes is the Finite Element Method (FEM), which offers time- and cost saving potentials in the design phase. In deep drawing, the use of a counter punch offers the possibility of extending the process limits. By superimposing compressive stresses on the workpiece, the initiation of cracks can be delayed, thus higher drawing ratios can be achieved. The aim of this research is therefore the numerical investigation of a deep drawing process with a counter punch to analyse the influence on the crack initiation and identify optimisation potentials for the process. For this cause, the applied force as well as the position and geometry of the counter punch are varied and the influence on fracture initiation is evaluated. It is found that the applied force on the counter punch is the major influencing factor for crack initiation. Furthermore, it was concluded that the contact between the counter punch and the workpiece should be applied as soon as the bottom of the cup is shaped. A further improvement can be achieved if the counter punch is geometrically adapted to the bottom of the workpiece.

Introduction

The process limits regarding fractures in deep drawing can be extended by reinforcing or relieving the force transfer zone. Reinforcement can be achieved either by increasing the initial sheet thickness or by using materials with higher strength [1]. Furthermore, locally adapted semi-finished products, such as tailored rolled blanks [2] can be used.

In order to relief the force transfer zone, the stress state can be influenced. Wu et al. [3] found that the formability of a sheet metal can be increased by superimposing a hydrostatic pressure on the material. In hydromechanical deep drawing, additional compressive stresses are realised by means of an active medium [4]. However, this is associated with significant higher tool costs and increased regulatory expenditure compared to conventional deep drawing, as it requires the integration of complex process technology into the tool set up.

Petzold and Otto [5] extended a deep drawing process by generating material flow from the outer part of the flange towards the developing cup. During forming, the material from the edge of the workpiece is pushed forward by a mechanical force, which is applied by a compression ring. In experimental tests, a significant increase in the applicable drawing ratio could be achieved. In

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addition, the reduction of the sheet thickness at the transition zone between the bottom and the wall could be reduced compared to conventional deep drawing.

Another possibility is deep drawing with a counter punch, where an additional punch is integrated into the conventional tool structure, which applies a force perpendicular to the bottom or both the bottom and the radius of the deep drawn cup. Morishita et al. [6] investigated the effect of a counter punch during deep drawing of tailored blanks, in which centrally welded blanks of different materials were deep-drawn into square cups. Experimental tests showed that the activation of a counterforce enables an increase in the achievable drawing height. While a cup height of less than 30 mm could be achieved in conventional deep drawing, a counterforce of 100 kN made it possible to produce cups with drawing heights of up to 60 mm without fracture.

A further investigation was carried out by Behrens et al. [7], where a counter punch was used during deep drawing of two high-strength steels HX340LAD and HCT600X. The counterforce was applied at the bottom and the radius of rectangular cups. It was found, that higher limiting drawing ratios can be achieved with the additional counter force, thus leading to an extension of the process window. Furthermore, in a recent study [8], deep drawing was performed with a flat counter punch which applies pressure only in the bottom of the cup. The extension of the process limits was achieved by higher applicable blank holder forces, which increased by 14.3% for HX340LAD and 17.9% for HCT600X. Additionally, the process was simulated and validated using the FE-software Abaqus to investigate the effect of the counter force, which was defined as a surface pressure field on the bottom of the cup. It was found that the stress state slightly shifts to lower stress triaxialities, thus allowing higher deformations to be reached.

Based on the aforementioned literature, this research investigates the influence of the counter punch numerically to evaluate the effect of the force on the stress state in the bottom of the cup and derive further optimisation potentials for industrial processes. For this purpose, deep drawing of two high-strength steels HX340LAD and HCT600X with and without the activated counter punch are simulated and the influence of varying process parameters on the fracture initiation is evaluated. In this study, the counter punch will be modelled as a deformable body instead of a pressure field, so that the friction to the workpiece is taken into account.

Materials and Methods

In order to investigate the influence of the superimposed force on fracture initiation, the deep drawing process was numerical depicted in Abaqus/Explicit. Fig. 1 a) shows the process set up. The tool system consists of a punch, a blank holder and the forming die, which were modelled as ideal rigid bodies and meshed with shell elements with an element edge length of 1.5 mm. For the application of the blank holder force, a uniform surface pressure was defined. With a thickness of 1 mm and initial dimensions of 281 mm x 213 mm, the sheet is formed to a final size of 160 mm x 80 mm, which corresponds to a deep-drawing ratio of 1.9. For the sheet, hexahedral elements with an element edge length of 1.5 mm were used, which were refined to 0.5 mm in the area of the bottom of the final cup. The forming punch moves with a constant velocity of 10 mm/s for a drawing depth of 55 mm. For the contact between the tools and the workpiece, a friction coefficient of 0.05 was defined on the basis of a previous study [9]. To minimize the computational effort, mass scaling with a factor of 100 and a time scaling factor of 10 were applied. Exemplary simulations with and without scaling were carried out for both materials to ensure that the application of the scaling factors has no significant influence on the results.

Materials Research Proceedings **25** (2023) 329-336 https://doi.org/10.21741/9781644902417-41

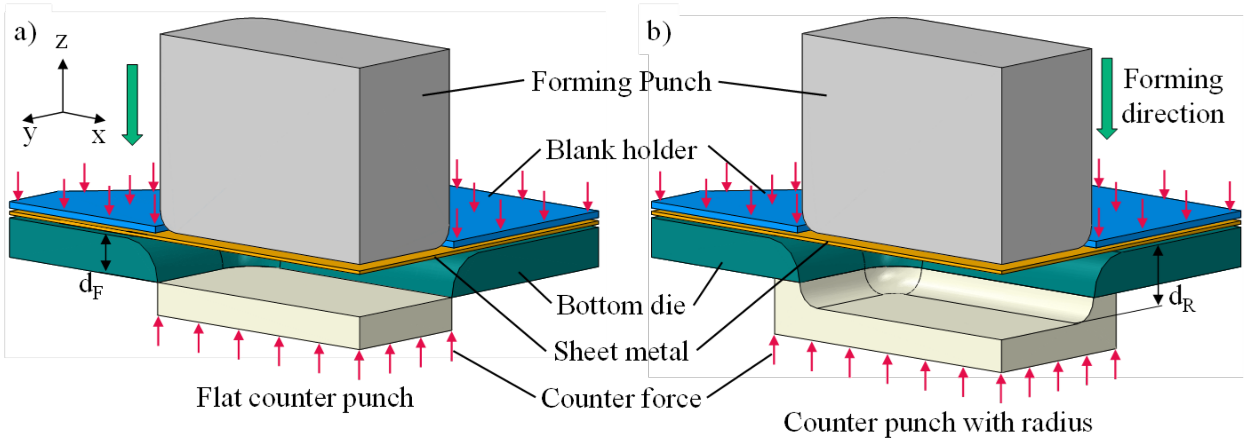

Fig. 1: Deep drawing model with a) flat counter punch and b) counter punch with radius

For the counter punch, which is located below the forming die, shell elements with an element edge length of 1.5 mm were used and an elastic material model with a Young's modulus of 210 GPa and a Poison's ratio of 0.3 was adopted. An ideal rigid behavior was not applicable, since numerical instabilities occurred when the sheet metal came in contact with the counter punch. The counterforce was induced by means of a surface pressure on the counter punch. In the experimental tool set up, the counterforce of 15 kN is applied by a gas pressure spring. Additional counterforces of 30 kN and 60 kN were defined in the numerical simulation to analyse the influence of the applied force. Moreover, the position of the counter punch was varied, so that it comes into contact with the sheet metal after a distance of d_f = 0 mm, 12 mm and 19 mm. At a distance of 12 mm, the flat counter punch is located directly under the die, which is shown in Fig. 1 a). Furthermore, a simulation was carried out in which the counter punch was designed with a radius to extend the contact area, which can be seen in Fig. 1 b). Due to the radius, however, the counter punch can only come into contact with the workpiece after a distance of at least d_R = 19 mm. Table 1 summarises the investigated process and geometrical parameters.

Table 1. Investigated parameters

Material	Blank holder force [kN]	Counter force [kN]	Distance [mm]	Counter punch geometry
HX340	320	15, 30, 60	12	Flat
		15	0, 12, 19	
			19	Flat, Radius
HCT600	230	15, 30, 60	12	Flat
		15	0, 12, 19	
			19	Flat, Radius

For the material modelling, elastic-plastic models of the high-strength steels HX340LAD and HCT600X were defined. The data was determined in a previous study by means of tensile and hydraulic bulge tests [9]. To model the flow curve, the approach of Gosh was chosen for HX340LAD and a combined approach of Swift and Hocket-Sherby for HCT600X, since these approaches ensured the best approximation of the experimental data. In addition, the flow criterion according to Hill'48 [10] was defined for both steels. The yield loci and flow curves with the corresponding model coefficients are shown in Fig. 2.

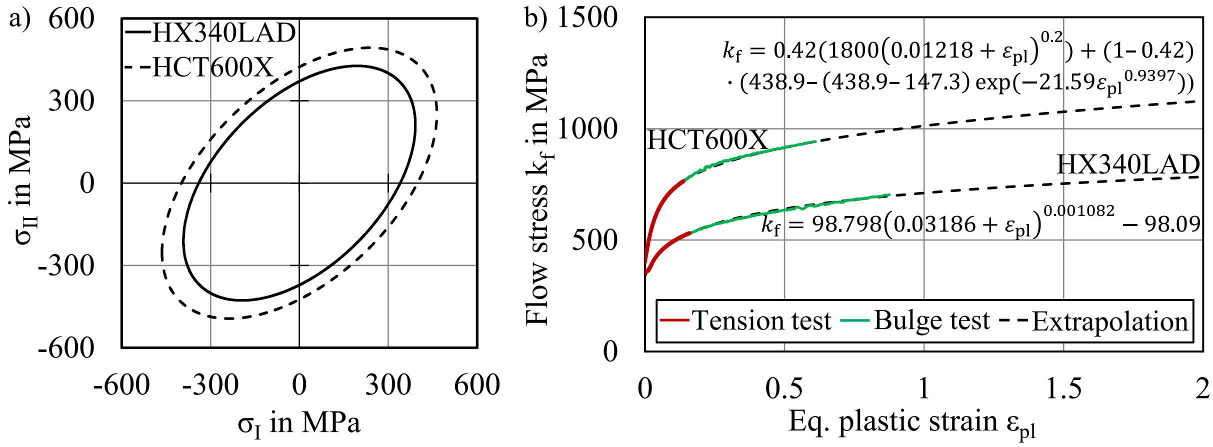

Fig. 2: Yield loci a) and flow curves b) for HX340LAD and HCT600X according to [10]

In order to predict the initiation of fracture during forming, the damage behaviour was modelled using the Modified Mohr-Coulomb (MMC) criterion [11], where the equivalent plastic strain at fracture $\varepsilon_{\mathrm{pl}}^{\mathrm{f}}$ is defined depending on the stress triaxiality η, normalised Lode angle $\bar{\theta}$, strain hardening exponent n and the material specific constants A, c_1, c_2, c_Θ^{s}, c_Θ^{ax}:

$$\varepsilon_{\mathrm{pl}}^{\mathrm{f}} = \left\{\frac{A}{c_2}\left[c_\Theta^{\mathrm{s}} + \frac{\sqrt{3}}{2-\sqrt{3}}\left(c_\Theta^{\mathrm{ax}} - c_\Theta^{\mathrm{s}}\right)\left(\sec\left(\frac{\bar{\theta}\pi}{6}\right) - 1\right)\right]\left[\sqrt{\frac{1+c_1^2}{3}}\cos\left(\frac{\bar{\theta}\pi}{6}\right) + c_1\left(\eta + \frac{1}{3}\sin\left(\frac{\bar{\theta}\pi}{6}\right)\right)\right]\right\}^{-1/n} \quad (1)$$

The MMC criterion was chosen because its applicability was proven for various ductile materials, such as aluminium alloys and high-strength steels [11]. Furthermore, the applicability for the materials considered in this research was verified in a previous study [12]. Therefore, tensile tests with butterfly specimens were carried out to determine the material specific constants. A special tooling system was used, which enables the variation of the force direction prior each test. This allowed different stress states ranging from shear to uniaxial tensile to be induced in the centre of the butterfly specimens. Afterwards, numerical simulations were used to evaluate the damage parameters $\varepsilon_{\mathrm{pl}}^{\mathrm{f}}$, η and $\bar{\theta}$ at the onset of fracture to calibrate the model parameters A, η, c_1 and c_2 by the least square method. For the parameters c_Θ^{s} and c_Θ^{ax}, the default values of one were assumed analogous to [11]. The resulting parameters are summarised in Table 2.

Table 2. Parameters of the used MMC criterion [13]

	A	n	c_1	c_2
HX340	713.0	0.165	0.208	401.934
HCT600	1018.6	0.143	0.166	560.033

In the simulation of deep drawing, the damage variable D is evaluated to predict the onset of fracture. D increases monotonically with the plastic strain $\varepsilon_{\mathrm{pl}}$ according to Eq. 2.

$$D = \int \frac{d\varepsilon_{\mathrm{pl}}}{\varepsilon_{\mathrm{pl}}^{\mathrm{f}}} \quad (2)$$

Material damage is present, when D reaches or exceeds the value of 1. The evolution of damage or the deletion of elements after failure is not taken into account in this study.

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Results

In order to validate the location of crack initiation, experimental deep drawing tests were carried out. As mentioned earlier, the experimental procedure is presented in detail in [8]. Fig. 3 a) shows an experimental cup made of HX340LAD, which was formed with a blank holder force of 320 kN and without a counter punch. In b), the numerical distribution of the damage variable D is shown. In the simulation, material damage is visible in the corner of the cup, where the damage variable D exceeds the value of 1 and is marked grey. Since no elements are deleted after failure and no fracture evolution is taken into account, the crack does not spread as intensively as in the experiment over the side of the cup. Nevertheless, the damage criterion provides good agreement with the experimental results regarding the location of fracture initiation in the corner of the cup.

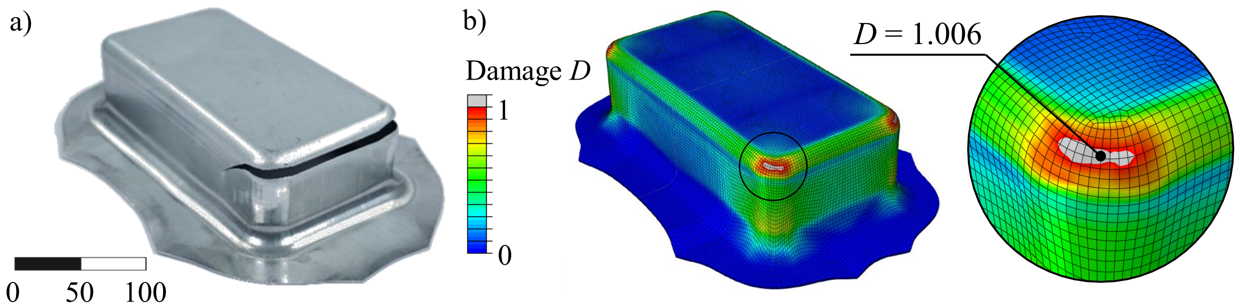

Fig. 3: Results without counter force: a) experimental cup made of HX340LAD with a blank holder force of 320 kN and b) distribution of damage from the simulation

In the next step, the experiment and simulation were carried out again with the flat counter punch at a distance of 12 mm and an applied counter force of 15 kN, while aforementioned parameters were kept constant. Fig. 4 compares an experimentally formed component with the numerical result of the simulation with a counter force of 15 kN.

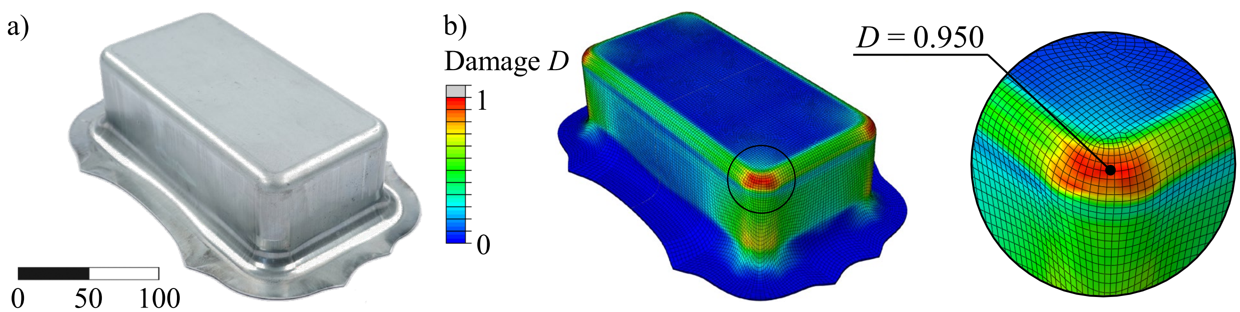

Fig. 4: Results with activated counter force of 15 kN: a) experimental cup made of HX340LAD with a blank holder force of 320 kN and b) distribution of damage from the simulation

It can be clearly seen, that the experimental component could be formed without any formation of cracks. Furthermore, no material damage is predicted by the simulation, which can be attributed to the influence of the counter punch. In order to evaluate the effect of the counter force more precisely, the course of the plastic strain over the stress triaxiality at the corner of the cup is shown in Fig. 5 a) for HX340LAD and in b) for HCT600X. Differing from the HX340LAD, a blank holder force of 230 kN is used for the HCT600X. Additional simulations with counter forces of 30 kN and 60 kN were carried out to analyse the influence of the applied force. The results represent the mean of 10 elements located in the fracture initiation area. Additionally, the mean damage D is indicated for each simulation.

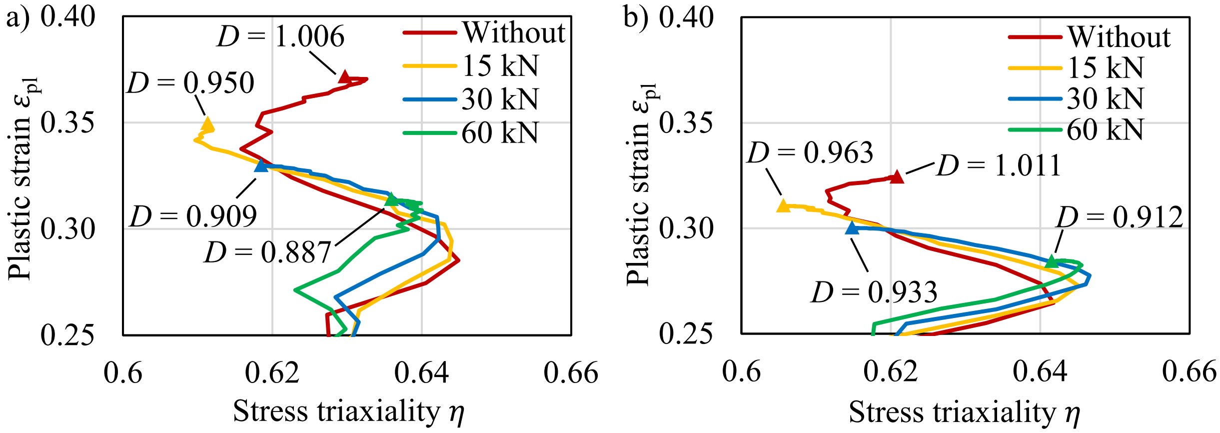

Fig. 5: Plastic strain over stress triaxiality depending on the counter force for a) HX340LAD and b) HCT600X

HX340LAD shows higher plastic strains due to a higher applied blank holder force. Thus, the effect of the counter punch is more significant than for HCT600X. However, for both materials, the increasing counter force leads to a reduction of the maximum plastic strain at the radius of the cup. This can presumably be attributed to the restraining frictional force between the sheet metal and the counter punch, which prevents the material from exceeding the forming limit and thus the formation of fractures. An increase of the counter force and therefore has a positive effect on fracture prevention. However, higher counter forces also increase the required press forces, which enhances the tool loads and potentially requires larger forming machines.

In the next step, the influence of the punch position was varied so that the sheet metal would come into contact with the counter punch after a distance of 0 mm, 12 mm and 19 mm. Here, the flat counter punch with constant force of 15 kN and blank holder forces of 320 kN for HX340LAD and 230 kN for HCT600X were applied. The results are shown in Fig. 6.

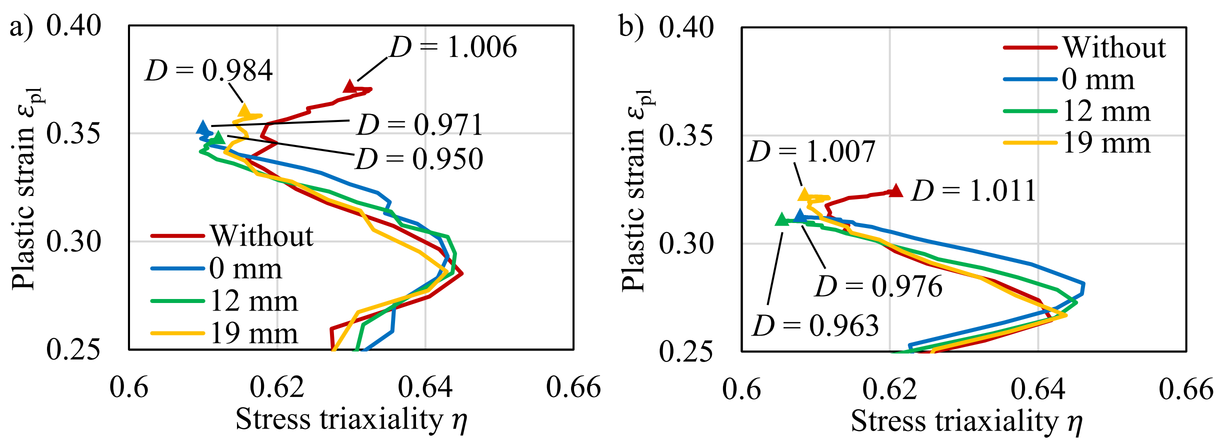

Fig. 6: Plastic strain over stress triaxiality depending on the punch distance for a) HX340LAD and b) HCT600X

For both materials, the best results are achieved with a distance of the counter punch of 12 mm. Shifting the counter punch to a distance of 0 mm does not reduce the resulting plastic strain compared to a distance of 12 mm and therefore does not diminish the risk of fractures. This concludes that the counter punch has no positive influence in the first phase of forming, when the radius of the cup is shaped around the radius of the forming punch.

Furthermore, if the sheet metal comes into contact with the counter punch after a distance of 19 mm, a higher increase in plastic strain can be seen, resulting in a closer approach to the forming capacity of the materials. It can even be seen that material failure is present for HCT600X, since the mean damage D exceeds the value 1. This leads to the conclusion that the sheet metal should come into contact when the bottom of the cup is shaped out, which is in the considered case a distance of 12 mm, to achieve an optimal effect on the fracture prevention.

Finally, the influence of the punch geometry was investigated. For this purpose, the flat counter punch was extended by a radius that merges tangentially into the edge of the forming die, which is shown in Fig. 1 b). The goal hereby was to increase the contact surface in the corner area of the workpiece. Fig. 7 shows the resulting plastic strain over the stress triaxiality and compares it to conventional deep drawing without counter force and deep drawing with a flat counter punch at a distance of 19 mm. Here, the counter force was again held constant at 15 kN and blank holder forces of 320 kN for HX340LAD and 230 kN for HCT600X were applied.

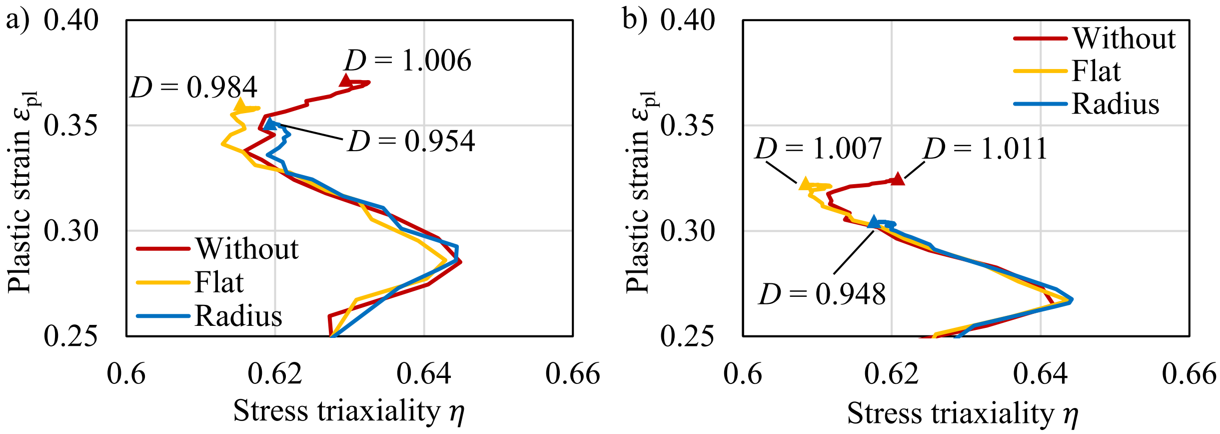

Fig. 7: Plastic strain over stress triaxiality depending on the punch geometry for a) HX340LAD and b) HCT600X

The use of a counter punch with a radius leads to a further reduction of the plastic strain compared to a flat counter punch for both materials. This can be attributed to the fact that the contact area was extended and the counter force could be applied in the most critical area for material damage. Therefore, the use of a counter punch that is geometrically adapted to the geometry of the workpiece has a positive effect on the prevention of fractures and thus on the extension of the process limits. However, the contact to the sheet metal can only be established after 19 mm due to the radius of the counter punch. Hence, similar results can be achieved with the flat counter punch, which comes in contact after a distance of 12 mm.

Summary and Outlook

In this work, the influence of a counter punch on the formation of cracks during deep drawing of two high-strength steels HX340LAD and HCT600X was investigated. It was found that the counterforce leads to a reduced plastic deformation in the bottom and radius of the cup and thus counteracts the initiation of fractures. As a result, higher blank holder forces and thus higher limiting drawing ratios can be achieved, which results in the extension of the process window. By means of numerical parameter studies, it was found that the highest influencing factor on fracture initiation is the force applied to the counter punch. As a result, the maximum force of 60 kN provided the best results in this research. Furthermore, it was found that the counter punch should come into contact with the workpiece as soon as the bottom of the cup is shaped, as this results in lower damage values compared to an earlier or later contact during the process. A further reduction of the damage could be achieved by a counter punch with a radius due to the increased contact area. But since the contact to the sheet can only be applied after a distance of 19 mm, only slight improvements could be achieved compared to a flat punch, which comes into contact after a distance of 12 mm. Therefore, the use of a flat counter punch is preferred in the considered process, as it less complex and simpler to implement into the tool system than a counter punch with radius.

In future investigations, the use of a counter punch should be applied in an industrial process to investigate the extension of the production limits. Furthermore, an economic feasibility study to weigh the benefits of the counter punch versus the additional costs due to a more complex tool design as well as higher required press forces would be beneficial.

Acknowledgements
The results presented were obtained in the project "Extension of the forming limits during deep drawing by additional force transmission" – 212270168. The authors thank the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) for their financial support.

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