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Study on the effects of tool design and process parameters on the robustness of deep drawing

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Abstract. In metal forming manufacturing processes, parameter fluctuations and an incomplete understanding of the process can lead to an undesirable deviation of the product properties from the required specifications and, therefore, affect the robustness of the process. In deep drawing, defects such as cracks and wrinkling can be linked to uncertainties within the process- and tool design parameters. To investigate the combined effects of these parameters on the quality of the finished product, simulation models are used to study the effects of parameter changes on the product quality. With the purpose of studying the effects of significant process and tool design parameters on the deep drawing process, a numerical parameter study is carried out based on a modular tool which allows for an investigation of process parameter variations within an adjustable parameter range of tool radii. While the material draw-in and the maximum punch force are used as quality indicators of the deep-drawing process, it could be shown that the elongation of the absolute length of the finished part can be used as an additional indicator for material thinning when observing the effects of the punch shoulder and die shoulder radii on the process robustness.

Introduction

The deep drawing process is the primary manufacturing process used in the automotive industry for the production of sheet metal components [1]. However, fluctuations of the process parameters as well as an incomplete understanding of the process can lead to deviations in the product properties from the required specifications [2]. Combined with the increasingly complex geometry in modern applications, the requirements on the robustness of the deep drawing process have become more challenging in recent years [3]. To define a safe process window and avoid wasting resources, it is necessary to understand the relationship between parameter fluctuations and defects such as cracks and wrinkles. While typical defects such as cracks and wrinkles are usually related to process parameters like blank holder force and the wear of the tool surfaces, the tool design parameters play a significant role within the development of defects and the thinning of the metal sheet [4, 5]. A thorough investigation of tool design and process parameters and their interactions can, therefore, help to achieve an increased robustness of the deep drawing process.

The effects of the process parameters and tool design parameters can be analyzed both experimentally and using finite element models. Experimental studies have the advantage of fully capturing the complexity of the forming process, whereas simulation models often rely on assumptions and simplifications, such as the material model or the modeling of the friction conditions. However, numerical investigations are significantly more time-efficient and allow for precise and flexible adjustment of the analyzed parameters as well as an easy extraction of parameters such as stresses and strains. [6, 7]

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Instead of looking directly into the material thinning or the defects that occur during deep drawing, investigations are often based on quality indices such as the punch force or the flange draw-in, which are accessible parameters during the deep drawing experiment. The flange draw-in is directly related to the material flow and, therefore, failure modes such as wrinkles or cracks [1]. It is also suitable for inline investigations such as closed-loop control systems in deep drawing [8]. Phenomena such as flange wrinkles and ironing can be identified and analyzed via the punch force curve, while the maximum punch force is one of the most relevant output parameters and commonly used to describe the deep drawing process. [9, 10]

The effects of process parameters on the deep drawing process are commonly studied using finite element models. The blank holder force has been identified to have a significant influence on the formation of wrinkles and cracks, as it can be used to control the material flow and thus influence the thinning of the material. Additional process parameters such as blank thickness, the friction coefficient and the temperature have been found to influence the deep drawing process, with the temperature affecting the effective stresses and the yield strength as well as the lubrication conditions [9, 11]. In reality, metal forming processes are subjected to uncertainties such as changing process conditions and varying process parameters. Changes in temperature, lubrications conditions and process parameters affect the process window and can therefore lead to failure of the finished product. To ensure that the deep drawing process is not negatively affected by the process uncertainties, the effects of both, tool design and process parameters need to be explained such that the parameters can be chosen in a way that ensures the quality of the produced parts, even if the process is subjected to uncertainties. [12]

The shoulder radii of the punch and die of the tool have a significant impact on the material flow, the thickness distribution of the blank and can even affect the earring height in cylindrical aluminum cups as well as wrinkle formation [11, 13]. Other studies were conducted on the influence of the tool geometry on the process robustness in micro deep-drawing [10, 14]. Besides cylindrical cup geometries, Chaimongkon et al. [15] studied the formability of aluminum sheet using a cross-die geometry which is used to resemble the complex strain paths and forming conditions of geometries formed in industrial applications. Kardan et al. [16] conducted both numerical and experimental studies on the influences of the shoulder radii of the tool with carbon steel as blank material. While he found that increase in the die shoulder radius decreases the punch force, an increase of the punch shoulder radius can either increase or decrease the punch force depending on the parameter space chosen for the punch shoulder radius. While the values for the shoulder radii have to be chosen with care, i.e. the die radius not being smaller than the die shoulder radius and the die shoulder radius being large enough to avoid the die cutting through the metal sheet, the optimal design of the tool depends on parameters such as the material, size and shape of the drawn part [4]. The mentioned significant parameters of the deep drawing process are shown in Fig. 1, where the geometry of the punch, die and finished part are demonstrated on a cylindrical cup geometry for visualization purposes.

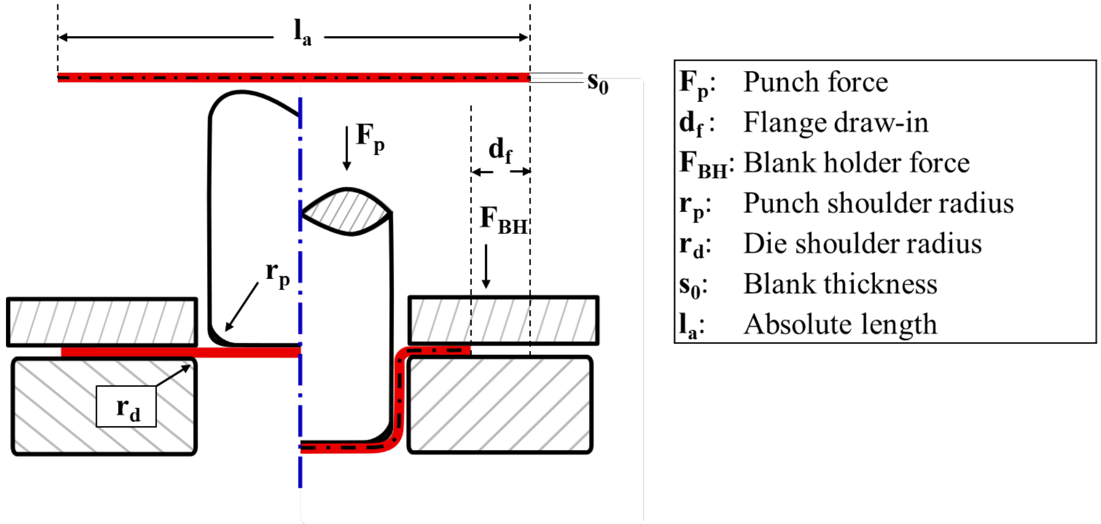

Fig. 1: Deep drawing process and parameters (based on [17])

Even if the influences of the parameters and the tool geometry on the deep drawing process are known, process failure often occurs in real production operations due to process fluctuations. Explainable modeling approaches of the stochastic process noise are needed in the design process of deep drawing tools to optimize the tool geometry. To pursue this goal, a modular deep drawing tool is developed in this paper to investigate the effects of the effective surfaces. This tool allows for the investigation of the robustness of the deep drawing process within a specified range of punch and die shoulder radius parameters, considering varying blank holder force values and variations of process conditions such as temperature and lubrication. A finite element model is used to analyze and explain the combined effects and interactions of the tool design parameters and the blank holder force on two quality indicators (maximum punch force and material draw-in). These numerical investigations form the basis for studying the influences of parameter fluctuations on the process limits associated with the die surface geometries and serve as a baseline investigation for future studies with the aim of developing guidelines for robust tool design. The study is carried out on a sheet metal cross die geometry to capture the complex nature of geometries in industrial applications.

Methodology

Modular tool. The numerical design of experiments with varying punch shoulder and die shoulder radii on a cross-die geometry is conducted based on a modular tool which allows for an independent exchange of the punch shoulder radii and die shoulder radii. Additionally, the punch, die, and blank holder are equipped with a temperature control system, which enables the analysis of temperature fluctuations on the deep drawing process in future studies. Modular tools have already successfully been developed making use of exchangeable inserts. Rigas and Merklein [18] used this approach to study different tool coatings while Özkaya [19] investigated oxidized inserts in dry deep drawing.

The tool used in this study is composed of three levels: the punch (bottom), the blank holder (center), and the die (top). Fig. 2 displays the top and bottom parts of the modular tool. The variation in the shoulder radius of the die is made possible by the modular design of the upper part of the tool, in which the dies are designed as inlays. In addition, holes for heating cartridges as well as thermocouples were provided in the punch, die, and blank holder. The developed tool can be extended by cross-punch inserts with any punch and die edge radii.

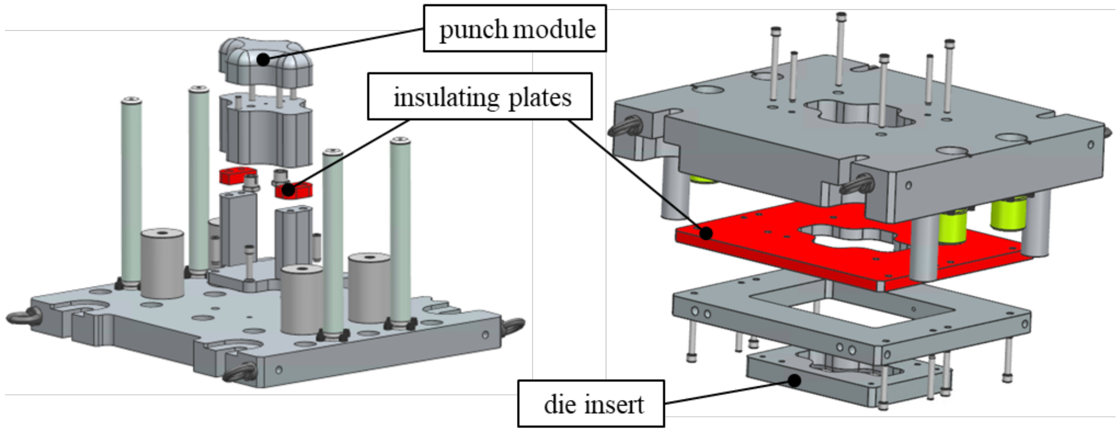

Fig. 2: Punch (left) and die (right) design of the modular tool

Finite Element Model. Finite element analysis was used in ABAQUS/Explicit to investigate the effects and interactions of the die shoulder and punch shoulder radii, as well as the blank holder force. The study is conducted on a steel cross-die geometry to examine strain states resembling the complex geometries used in the automotive industry [15]. In the finite element model, only a quarter of the cross-die geometry was used due to its symmetry across the X and Y planes, on which symmetric boundary conditions were applied in the model. The punch, die, and blank holder are modeled as discrete rigid bodies, while the blank is modeled as a flexible body consisting of approximately 25,000 solid elements (C3D8R). Material parameters were determined using a tensile test and implemented with the anisotropic behavior being modeled using the Hill stress potential, with R_{22}= 1.0182, R_{33}= 1.2976 and R_{12} = 1.0723. The contact between the tool and the blank is modeled with kinematic contact and finite sliding conditions. Fig. 3 displays the finite element model parts and the meshed blank in its final state.

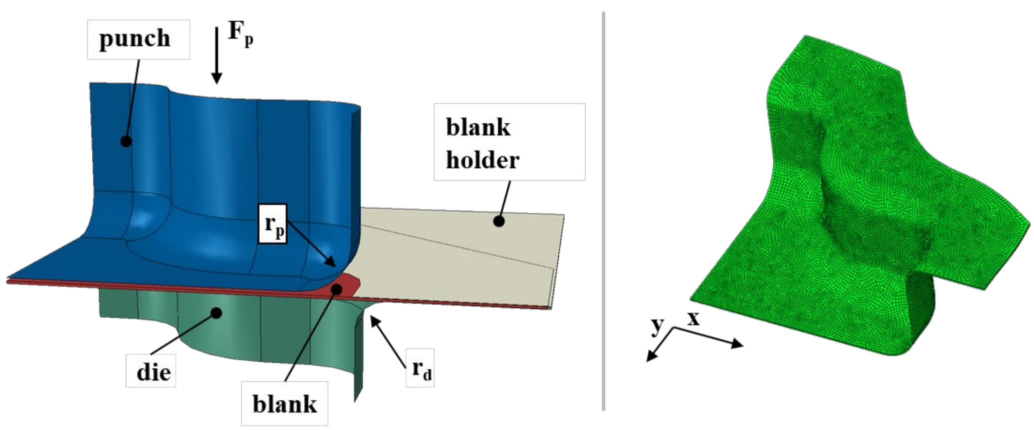

Fig. 3: Finite element model components (left) and mesh in final state (right)

The friction coefficient of the initial model is used as a tuning parameter for fitting the punch forces determined by the simulation model and the experiment, which results in a friction coefficient of μ=0.05. The model is then validated using the draw-in in the x-direction, with the numerical and the experimental result showing a deviation of less than 5%. Moving forward, the punch force and the draw-in in x-direction are used as output parameters for the Design of Experiments (DoE) campaign.

Effect analysis. To further investigate the influences of the tool design on the deep drawing process, two design parameters (punch shoulder and die shoulder radius) were varied alongside one process parameter (blank holder force), which was chosen for having a high influence on the punch force and the material thinning and, therefore, on the failure modes such as cracks and

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wrinkling. The effects on the output parameters as well as the interactions are investigated using three levels for every parameter to account for possible nonlinear relationships. Using a full factorial DoE, i.e. a set of experiments, in which every level of a parameter is combined with each level of the remaining parameters, results in a total of 27 simulations and ensures that nonlinear effects can be observed [20]. The levels for each of the three parameters are chosen by setting the values used in the initial, validated model as the center point and then ensuring an equidistant spacing between the minimum and maximum level. The resulting levels for the input parameter can be found in Table 1.

Table 1: Levels for die shoulder radius, punch shoulder radius and blank holder force

Parameter	Min	Center	Max
Die radius r_d	**8 mm**	**10 mm**	**12 mm**
Punch radius r_p	**16 mm**	**20 mm**	**24 mm**
Blank holder force F_{BH}	**278 kN**	**309 kN**	**340 kN**

Results and discussion

Results. After the simulations are conducted the effects of the varying parameters, i.e. factors, on the draw-in and the maximum punch force are determined. The effect is calculated from the change in the average of the output parameters at a certain level of each input parameter under consideration. For example, the effect of the die shoulder radius changing from 8 mm to 10 mm on the draw-in is calculated from the change of the mean draw-in values resulting from all experiments conducted with r_d=10 mm and all experiments conducted with r_d=8 mm [20]. Fig. 4 shows the effect plots of the die and punch shoulder and the blank holder force on the draw-in of the flange and the punch force.

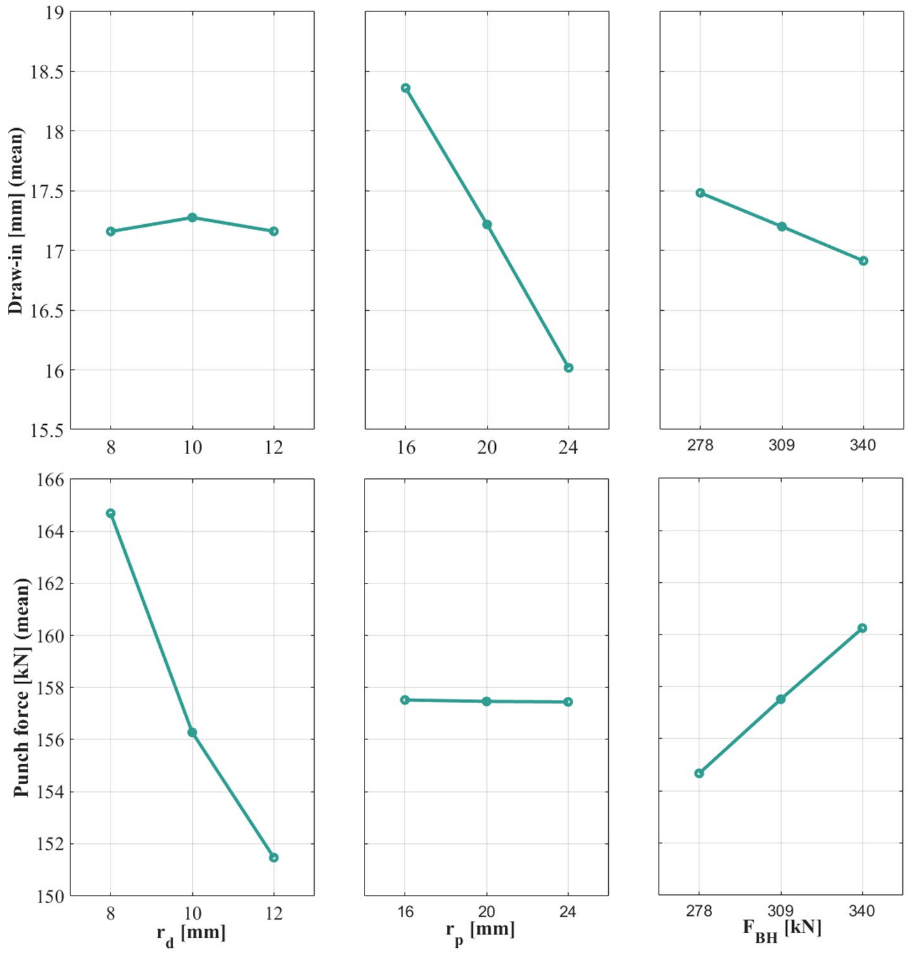

Fig. 4: Effects on draw-in and maximum punch force

It can be observed that the punch shoulder radius has a significant, linear influence on the draw-in, where increasing the punch shoulder radius leads to a smaller draw-in which indicates less material flow. A similar relation can be observed regarding the blank holder force, but with a smaller impact on the draw-in. The die shoulder radius tends to affect the draw-in nonlinearly, by increasing the draw-in when increased to 10 mm but decreasing it when again increased to 12 mm. The effect itself is overall insignificant and more datapoints are needed to further investigate it. Furthermore, an increase in the blank holder force increases the punch force linearly to a moderate extend. An increased die shoulder radius leads to a significant drop of the punch force, where the effect is more dominant for lower radii and, therefore shows a nonlinear relation between the punch force and the die shoulder radius. The punch radius has a negligible influence on the punch force with a linear trend. In summary, the die shoulder radius affects the punch force notably, while the effects of the punch shoulder radius are way less pronounced.

While the main effects show the relation between the input and output parameters, it should also be investigated whether the parameters influence each other, i.e. if the effects of the input parameters are cross-dependent. For that purpose, the interactions of the parameters are shown in Fig. 5 wherein each column shows the effects of one of the three input parameters on the corresponding output parameter (maximum punch force and draw-in).

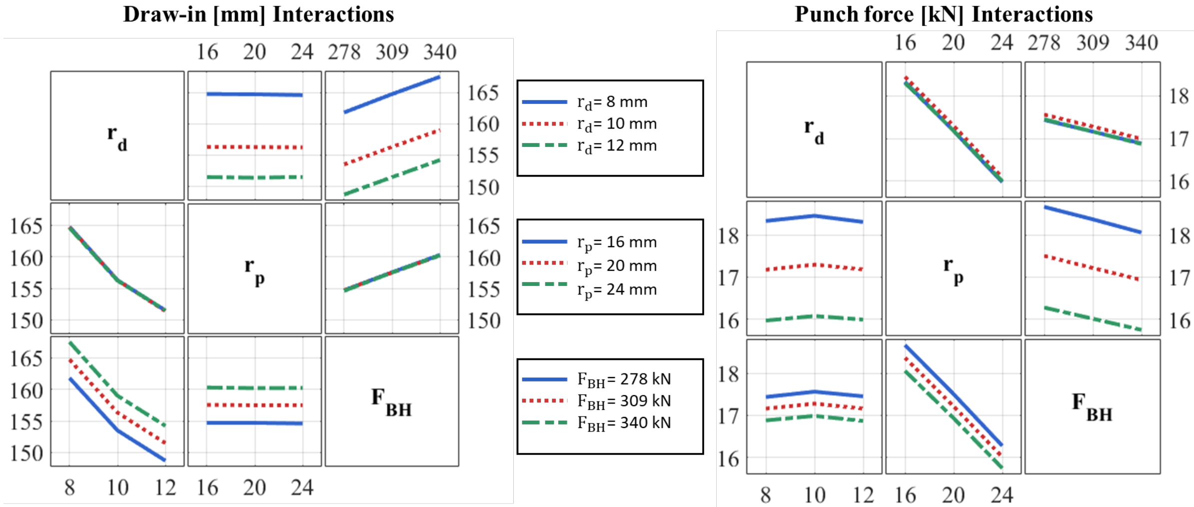

Fig. 5: Interaction plot of draw-in and the maximum punch force

Upon examining the interaction plot for the draw-in, it is evident that there are no significant interactions between the parameters. The effects of each parameter remain consistent when the remaining two parameters are varied, and the absolute deviations of the lines correspond to the main effects of the respective parameters. It can be noted that, within the examined parameter range, the punch shoulder radius has no significant effects or interactions reactions regarding the punch force.

Discussion. Since the parameters show no cross-dependencies within the examined parameter range, their impacts on the process robustness are discussed with assumed independence from each other. The effect analysis shows that higher punch shoulder radii lead to a lower draw-in, while an increase in die shoulder radii result in a decrease in the punch force. In summary, the die shoulder radius affects the punch force notably, while the effects of the punch shoulder radius are much less pronounced. During the forming process, the sheet is being subjected to continuous double bending stresses at the die curvature, which explains the die shoulder radius having a significant influence on the punch force. An increase of the blank holder leads to a lower draw-in as well as a higher punch force. The effects of the blank holder force can be explained by controlling the material flow. The friction coefficient between the blank holder, die and blank creates a tangential force that counteracts the flow of material. High blank holder force values increase the risk of tearing, while low values can cause wrinkles. [1, 4]

The observed effects of the punch shoulder radius on the draw-in and the maximum punch force are supported by studies conducted by Lee [21] as well as Moshksar [22]. Behrens et al. [14] found an increase in die shoulder radius to decrease the maximum punch force, and explains the effect with the increased back bending, with the back bending force being inversely proportional to the die radius, which also leads to reduced stresses in back bending, with larger die radii. However, the risk of wrinkling formations should be taken into account with increased die radii, since the contact area of the blank holder on the blank is reduced [23]. Furthermore, Qin et al. [5] explains that the change in the surface area of the finished part influences the effect of the die shoulder radius on material thinning and should, therefore, be taken into account when evaluating the robustness of the process. For these reasons, the influence of the punch shoulder and die shoulder radii on the robustness of the deep drawing process based on the chosen quality indices is investigated by examining the elongation of the absolute length l_a of the blank as well as the maximum stresses and equivalent plastic strains in the finished part, which are depicted in Fig. 6. The elongation of half of the absolute length in x-direction (l_{ax}) is taken as a measure for the increase of the surface area of the finished part, whereas the stresses and equivalent plastic strains are assumed to be an indication of an increased risk of material thinning.

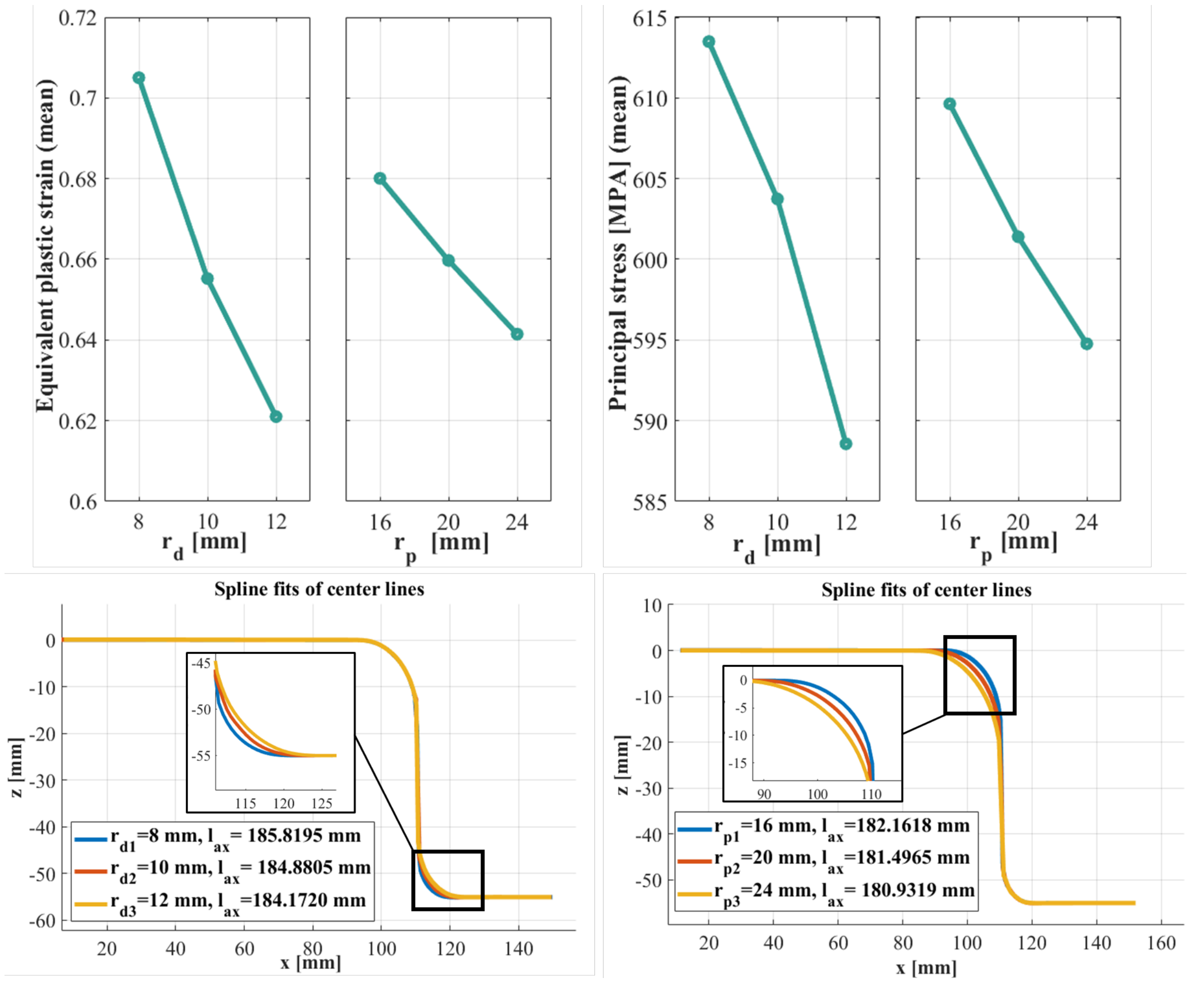

Fig. 6: Effect of punch radius on maximum stresses, equivalent plastic strain and elongation of the absolute length

It can be shown that an increase in punch shoulder radii decreases the absolute length of the finished part and decreases the maximum stress and plastic strain within the metal sheet, which is found near the area of back bending in the finished part. The same trend can be observed with the increase of the die shoulder radii. It can be shown that, while the reduction in the maximum punch force for higher die shoulder radii serves as a reliable indicator for a lowered risk of material thinning, i.e. lower stresses and plastic strain, the increase of draw-in for lower die radii indicates a more robust process, while the stresses and plastic strains increase in the finished part. Therefore, the absolute length and thus the surface area of the finished part should be considered when accessing the robustness of the deep drawing process.

Summary

The aim of this study was to investigate the dependence of the deep drawing process on the variation of the blank holder force in combination with the effects of a varying range of tool radii. For that purpose, a simulation model was developed based on a modular deep drawing tool to conduct a parameter study and study the effects and interactions of the tool shoulder radii and blank holder force. It could be demonstrated that the punch shoulder radius has a dominant effect on the material draw-in within the investigated parameter range of the tool, while the die shoulder radius has a significant influence on the punch force. Smaller punch shoulder radii result in increased material draw-in, while smaller die shoulder radii result in an increased punch force. An increase of the shoulder radii has been found to increase the risk of material thinning, which is indicated by increased maximum stresses and equivalent plastic strains. The material thinning is suggested to be related to an increase of the absolute length which is used as a measure for in the surface area of the finished part. It is found that the absolute length of the finished part, which is related to its surface area, can be used as an indicator for material thinning and should therefore be taken into account when relating the tool geometry to the robustness of the deep drawing process. The presented results will be used as a basis for experimental studies with varying process conditions with the goal to determine guidelines for a robust tool design.

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References

[1] Schuler GmbH, Metal forming handbook, Springer-Verlag, Berlin, New York, 1998.

[2] J.M. Allwood, S.R. Duncan, J. Cao, P. Groche, G. Hirt, B. Kinsey, T. Kuboki, M. Liewald, A. Sterzing, A.E. Tekkaya, Closed-loop control of product properties in metal forming, CIRP Annals 65 (2016) 573–596. https://doi.org/10.1016/j.cirp.2016.06.002

[3] F. Henning, E. Moeller (Eds.), Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung, second., überarbeitete und erweiterte Auflage, Hanser, München, 2020.

[4] F. Klocke, Manufacturing Processes 4, Springer Berlin Heidelberg, Berlin, Heidelberg, 2013. https://doi.org/10.1007/978-3-642-36772-4

[5] S. Qin, H.M. Shang, C.J. Tay, J.X. Mo, On the extent of stretching during deep drawing, Journal of Materials Processing Technology 59 (1996) 386–390. https://doi.org/10.1016/0924-0136(95)02169-8

[6] A. Birkert, S. Haage, M. Straub, Umformtechnische Herstellung komplexer Karosserieteile, Springer Berlin Heidelberg, Berlin, Heidelberg, 2013. https://doi.org/10.1007/978-3-642-34670-5

[7] Z. Marciniak, J.L. Dunca, S.J. Hu, Mechanics of sheet metal forming, secondnd ed., Elsevier Butterworth-Heinemann, Oxford, 2002.

[8] K. Siegert, E. Dannenmann, S. Wagner, A. Galaiko, Closed-Loop Control System for Blank Holder Forces in Deep Drawing, CIRP Annals 44 (1995) 251–254. https://doi.org/10.1016/S0007-8506(07)62319-1

[9] K. Chen, A. Breunig, J. Ha, B.L. Kinsey, P. Groche, Y.P. Korkolis, Robustness of deep-drawing finite-element simulations to process variations, Int J Mater Form 15 (2022). https://doi.org/10.1007/s12289-022-01695-3

[10] G. Behrens, F. Vollertsen, Influence of Tool Geometry Variation on the Punch Force in Micro Deep Drawing, KEM 554-557 (2013) 1306–1311. https://doi.org/10.4028/www.scientific.net/KEM.554-557.1306

[11] P.R. Tiwari, A. Rathore, M.G. Bodkhe, Factors affecting the deep drawing process – A review, Materials Today: Proceedings 56 (2022) 2902–2908. https://doi.org/10.1016/j.matpr.2021.10.189

[12] M. Liewald, T. Bergs, P. Groche, B.-A. Behrens, D. Briesenick, M. Müller, P. Niemietz, C. Kubik, F. Müller, Perspectives on data-driven models and its potentials in metal forming and

blanking technologies, Prod. Eng. Res. Devel. 16 (2022) 607–625. https://doi.org/10.1007/s11740-022-01115-0

[13] K. Bouchaâla, M.F. Ghanameh, M. Faqir, M. Mada, E. Essadiqi, Numerical investigation of the effect of punch corner radius and die shoulder radius on the flange earrings for AA1050 and AA1100 aluminum alloys in cylindrical deep drawing process, Heliyon 7 (2021) e06662. https://doi.org/10.1016/j.heliyon.2021.e06662

[14] G. Behrens, M. Ruhe, H. Tetzel, F. Vollertsen, Effect of tool geometry variations on the punch force in micro deep drawing of rectangular components, Prod. Eng. Res. Devel. 9 (2015) 195–201. https://doi.org/10.1007/s11740-015-0604-0

[15] T. Chaimongkon, S. Panich, V. Uthaisangsuk, Anisotropic fracture forming limit curve and its applications for sheet metal forming with complex strain paths of aluminum sheet, Int J Adv Manuf Technol 115 (2021) 3553–3577. https://doi.org/10.1007/s00170-021-07357-z

[16] M. Kardan, A. Parvizi, A. Askari, Experimental and Finite Element Results for Optimization of Punch Force and Thickness Distribution in Deep Drawing Process, Arab J Sci Eng 43 (2018) 1165–1175. https://doi.org/10.1007/s13369-017-2783-9

[17] E. Doege, B.-A. Behrens, Handbuch Umformtechnik: Grundlagen, Technologien, Maschinen, third. Aufl. twentiethsixteenth, Springer Berlin Heidelberg, Berlin, Heidelberg, 2016. https://doi.org/10.1007/978-3-662-43891-6

[18] N. Rigas, M. Merklein, Characterization of the Tribological Behavior of Different Tool Coatings and Dry Lubricant for High-Strength Aluminum Alloys at Elevated Temperatures, Adv Eng Mater 25 (2023). https://doi.org/10.1002/adem.202201650

[19] F. Özkaya, Development of a tool concept with selectively oxidised inserts for dry deep drawing (2019).

[20] K. Siebertz, D. van Bebber, T. Hochkirchen, Statistische Versuchsplanung, Springer Berlin Heidelberg, Berlin, Heidelberg, 2017. https://doi.org/10.1007/978-3-662-55743-3

[21] P.K.-S. Lee, An Analysis of the Effect of Process Parameters on the Formability of Sheet Metal. Dissertation, Birmingham, 1972.

[22] M. Moshksar, A. Zamanian, Optimization of the tool geometry in the deep drawing of aluminium, Journal of Materials Processing Technology 72 (1997) 363–370. https://doi.org/10.1016/S0924-0136(97)00196-9

[23] G. Behrens, F.O. Trier, H. Tetzel, F. Vollertsen, Influence of tool geometry variations on the limiting drawing ratio in micro deep drawing, Int J Mater Form 9 (2016) 253–258. https://doi.org/10.1007/s12289-015-1228-9