Optimisation of the blank holder stiffness in deep drawing processes by using FEA

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Abstract

When deep drawing sheet metal components having complex geometries, varying thicknesses of materials occur in the flange area. Extreme thickening of the part flange will cause pressure peaks and therefore increased restraining forces being applied onto the contact surface between blank holder and part occur. This undesired effect during deep drawing will reduce process window and process robustness as well. In this paper, a new approach to optimise the blank holder stiffness in deep drawing process is presented. In this case the blank holder consists of one cover plate which is supported by numerous appropriate elastic elements made of cast iron. Stiffness of the blank holder as well as pressure distribution during deep drawing was optimised by varying elasticity and order of the supporting elements in real trials. For this purpose simulation and experimental investigation of car fender geometry were accomplished.

Blank holder plate and corresponding supporting elements were meshed with solid elements and considered as elastic bodies in FEA. Deep drawing was simulated systematically with different FE-Models using LS-Dyna software code. Simulation results were compared with measurements obtained by experiment, and they were found in good accordance to each other.

Simulation and experimental results showed that with optimised blank holder stiffness, the wrinkles of second order as well as crack tendency in deep drawing process can be significantly reduced when calculating optimal blank holder stiffness for die assembly. Due to that, the process window for such deep drawing process was enlarged.

Key words: deep drawing, blank holder, wrinkles, cracks.

1 Introduction

Nowadays, the automotive industry is challenged by increasing environmental regulations as well as permanent enhancement of the standard requirements regarding passengers' safety. One possibility to decrease fuel consumption and carbon dioxide emissions of the vehicles is to reduce the weight of the car body. The capability to absorb emerging dynamic loads of a car body during its use, especially in crash events, is one of the key design requirements for car body structures. The use of high and advanced high strength steels for manufacturing the desired car body parts allows exceptional opportunities for reducing the weight (by using thinner sheet metals) as well as increasing the crash performance of the vehicle [7]. It is necessary to emphasize that the high strength steels (HSS) do have very high levels of tensile strengths at relatively low values of elongation at fracture as well as relatively low anisotropy values. These mechanical properties indicate that HSS usually do have strong tendencies towards wrinkling, very small formability when compared to mild steels, and tremendous elastic recovery or spring back [6]. Due to that, the use of high strength steels for forming complex part geometries is increasing problems in the manufacturing process which have been existing for a while such as quality control requirements and process robustness. Considering previously defined influencing factors, the process window in deep drawing for that very reason in fact become smaller. Within this small process window, the parts regarding quality requirements with low scattering have to be manufactured [8]. It is well known that the blank holder design has a very important influence on crack and wrinkle emergence in deep drawing processes. During deep drawing processes, the blank is clamped between blank holder and die. The main purpose of the blank holder is to avoid the wrinkling occurrence and to induce the necessary restraining force. Due to changeable sheet thickening during deep drawing, extreme pressure (pressure peaks) at the contact surface between blank holder and part can occur. This occurrence will stop material draw-in in this area, and due to that cracks will arise (Fig. 1a). On the other hand, very low pressures between blank holder and part will cause wrinkle formation (Fig. 1b). Due to that, it is necessary to optimise blank holder structure aiming at reduction of the tendency towards wrinkles and cracks.

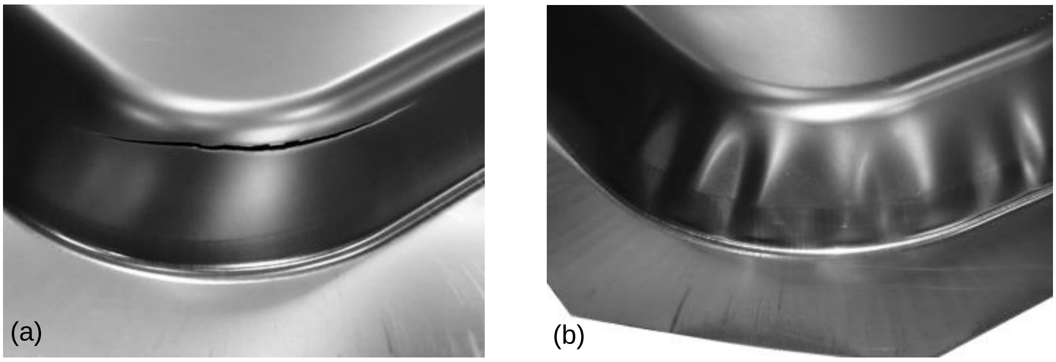

Fig. 1: Influence of the pressure distribution on part surface quality in deep drawing process; (a) high pressure in the part edge area (cracks), (b) low pressure (wrinkles of the second order)

With the goal of increasing part surface quality and improving process robustness by influencing the local blank holder stiffness, simulative and experimental investigation for one car fender geometry have been accomplished in this paper.

2 Control of the sheet metal draw-in

Objecting a robust deep drawing process of high quality parts, the influence of material draw-in is of great importance [2]. By changing the blank material draw-in it becomes possible to influence crack occurrence as well as wrinkle formation. Some of the possibilities to control material draw-in are listed below:

- Spotting of the tool surfaces,
- Variation of the blank shape,
- Changeable tribological conditions in the contact area between blank, blank holder and die,
- Use of the appropriate shape of draw beads,
- Changeable surface pressures between blank holder and part flange,
- Use of the multi-point cushion system [9].

The process window in deep drawing processes can be increased by spotting of the tool surfaces, which is done manually during the testing phase. After the forming tool is manufactured, it is necessary to spend additional time in order to improve tool surfaces which will give satisfied part shape quality as well as process robustness. Also, this additional work will significantly increase tool manufacturing costs. Draw beads are usually used to affect material draw-in when forming parts with complex geometries [1]. The main aim of their use is to locally increase restraining force. In order to affect material draw-in, the stiffness of the blank holder was optimised during the tests which have been carried out regarding this paper. In this investigation the blank shape was not changed and the deep drawing tool without integrated draw beads was considered. The tool used here was designed for a single-acting press. The blank holder consists of one plate which is supported by numerous elements made of steel and cast iron. It was possible to influence the contact pressure in the part flange area by changing elasticity and arrangement of the supporting elements.

3 Wrinkle Formation Process

Recent experimental and simulation results at the Institute for Metal Forming Technology (IFU) Stuttgart showed that it is possible to describe wrinkle formation process regarding to change of compressive stresses during deep drawing process. Fig. 2 shows relationship between compressive stress and drawing depth. It can be assumed that the second principle stress is in compression (A-B1 area in Fig. 2) at the beginning of the wrinkle formation process [4]. After the wrinkle initiation process is finished, value of the compression stress starts to reduce (B2-C area). The second principal stress achieves its maximum value during the wrinkle initiation process (phase between B1 to B2). During this phase, the value of compression stress is approximately constant. After the point in the time B2, the compression stress tends towards the value zero. It is assumed that in time point C, the wrinkle formation process is finished. After point C a double tensile stress state occurs in the wrinkling area. Thus, according to the change of compression stress, the wrinkling process can be divided into four phases [5]:

1. Safe area (A-B)
2. Wrinkle initiation (B-B2)
3. Growth of the wrinkle (B2-C)
4. Wrinkle formation is finished (after C)

The wrinkling process can be evaluated according to four parameters α, β, L and σ^{cr} (Fig. 2):
1. α: Growth rate of compression stress
2. β: Growth rate of the wrinkle
3. L: Phase of the wrinkle initiation
4. σ^{cr}: Critical compression stress

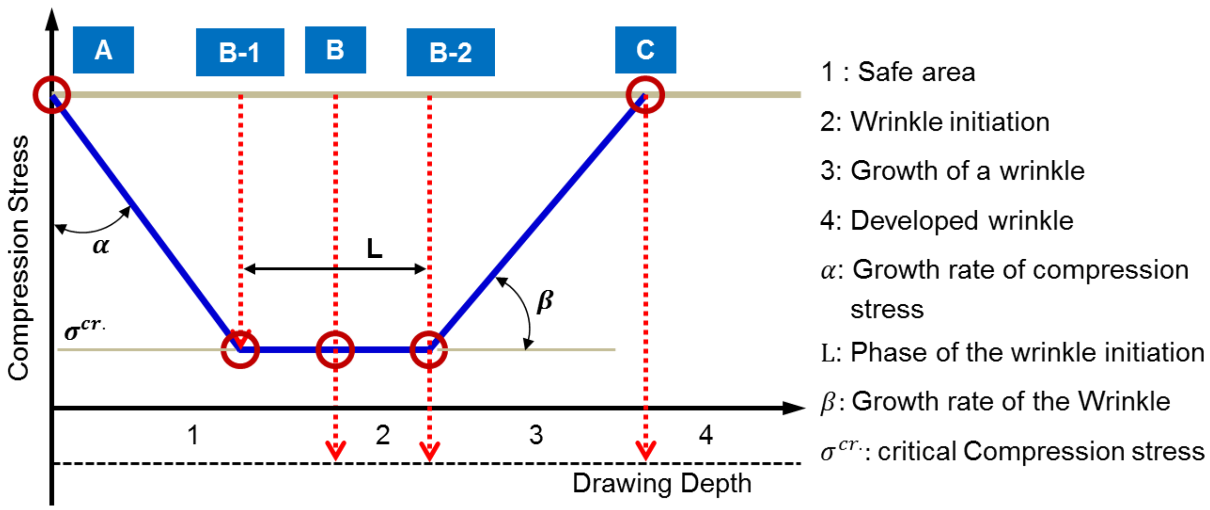

Fig. 2: Simplified wrinkling formation process

4 FEM-Model for deep drawing process

Main aim of the FEM simulation is prediction of the wrinkle formation, crack tendency, material draw-in as well as possible part shape deviations in forming process. In case of FE simulation of deep drawing process, the tool active surfaces are usually modelled as rigid body elements. But in reality, the tool has an elastic body. In this case elasticity of the tool and press can be adjusted approximately by appropriate contact definition.
Due to this simplification difference between simulation and experimental results can occur. In order to increase simulation preciseness, the tool and the press altogether should be modelled as an elastic body. This will result in a tremendously increased simulation time. Within this investigation, simulation of deep drawing process for one car fender geometry considering the rigid tool surfaces as well as elastic tool bodies was carried out.

4.1 FEM-Model for a rigid blank holder

Deep drawing process was simulated by using the FE-Code LS-Dyna. First, the deep drawing simulation of one car fender geometry using a rigid tool (punch, die and blank holder) was carried out. The tool geometry is meshed with the shell elements type Belytschko-Tsay Shell (ELFORM 2). For all tool parts, material model “MAT_RIGID” was applied. For the punch and die, the contact type *CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE with soft constraint 4 was applied. The contact type *CONTACT_FORMING_SURFACE_TO_SURFACE with soft constraint 0 is used to describe the contact between blank holder and blank. The blank was meshed with the shell elements type Belytschko-Tsay Shell (ELFORM 2).
In the simulation for blank, material model *MAT_36 (3-Parameter Barlat Plasticity) was used. This material model enables implementation of Lankford parameters r_0, r_{45} and r_{90} into FEM-Model and due to that include variety of material parameters depending on rolling direction [3]. Material properties for the blank material (HC 340 LAD) with the thickness of 1.0 mm were obtained from an uniaxial tensile test. Flow curve was approximated by using the Swift rule. Dimension of the car fender geometry is approximately 644 mm and width was set to 385 mm. Fig. 3 shows the FEM-Model for deep drawing process considering the rigid tool surfaces.

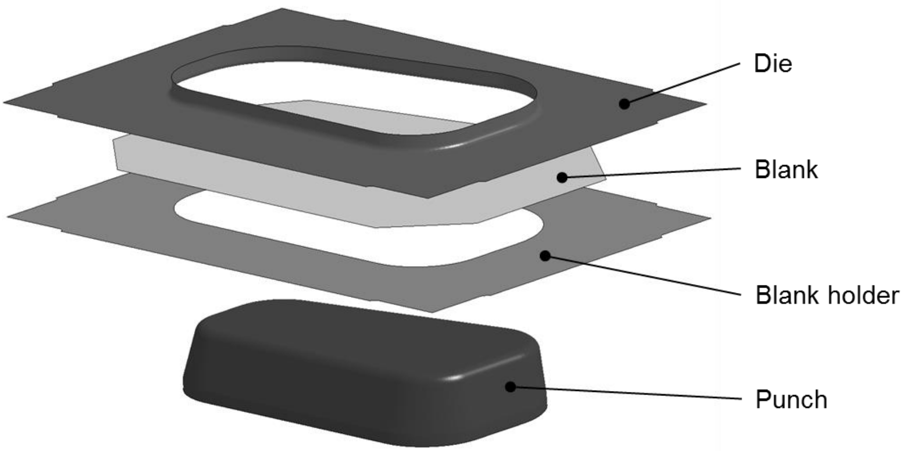

Fig. 3: FEM-Model for deep drawing process using a rigid blank holder

4.2 Simulation results when using the rigid tool

For analysis of the simulation results, different aspects were taken into account. Occurring stresses and strains in combination with the Forming Limit Diagram (FLD) were evaluated. Compressive stresses were analysed in the sidewall of the parts in order to define the start of the wrinkle formation regarding different forming conditions.

Fig. 4 shows simulation results for deep drawing by using the rigid tool components. Applied blank holder force in this case was 900 kN and deep drawing depth was set to 60 mm. Here, two finite elements were selected in the critical area of the part regarding occurrence of wrinkles (Fig. 4a). In order to analyse wrinkle formation process, a diagram which defines dependency of minimum principal stress (compressive stresses) and deep drawing depth is presented (Fig. 4b). It can be seen that the wrinkle is initiated at the deep drawing depth of approximately 17 mm.

Wrinkle initiation process took up to drawing depth of 40 mm for element "1" and up to depth of 35 mm for element "2". During these two defined points in the diagram, the compressive stress starts to reduce continuously. At the achieved drawing depth of approximately 57 mm the minimum principal stress is very close to value 0. Regarding the previously described assumption, at this deep drawing depth wrinkle is completely formed for finite element "2".

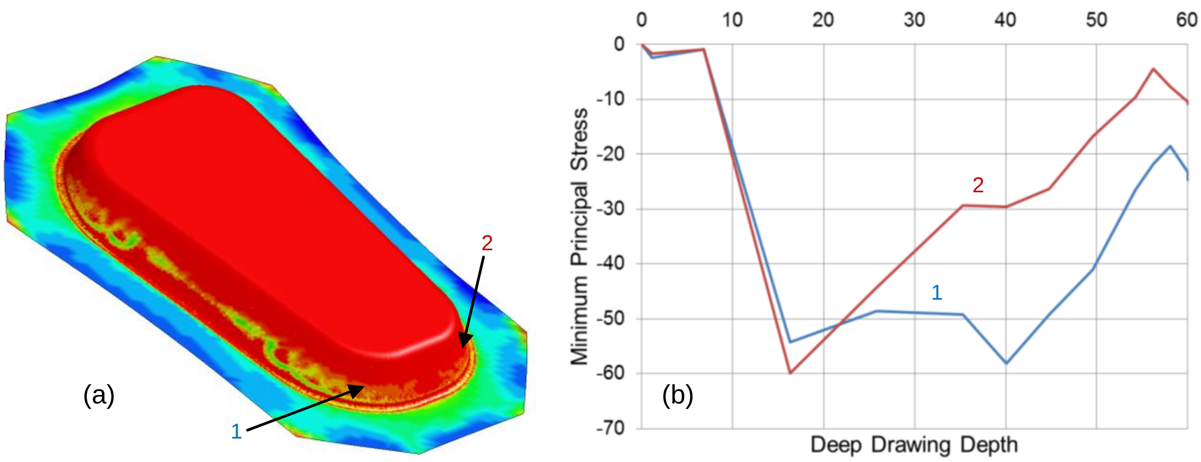

Fig. 4: Analysis of the compressive stress distribution; (a) selected elements of formed part shape, (b) relationship between minimum principal stress and deep drawing depth

The simulation results showed an increased tendency for wrinkle formation. One possibility to reduce wrinkle tendency was to apply bigger blank holder force or to change contact description in the contact area between blank and active tool surfaces. Here it should be considered that applying a bigger blank holder force increases risks of sheet thinning as well as crack arising.

Fig. 5 shows simulation results for deep drawing process with bigger blank holder force. The applied blank holder force in this case was 1050 kN. As portrayed earlier in the example before, part height in this case was set to 60 mm. Simulation results for previously defined forming conditions showed a

reduced tendency for wrinkle formation. For lower applied blank holder force and the same deep drawing depth simulation results showed an increased tendency for wrinkle formation. In Fig. 5a it can be seen that the shell thickness at the part bottom edges (marked in red) is reduced extremely.
Due to that, it can be assumed that application of higher blank holder force will lead to arising of the cracks in that part area.

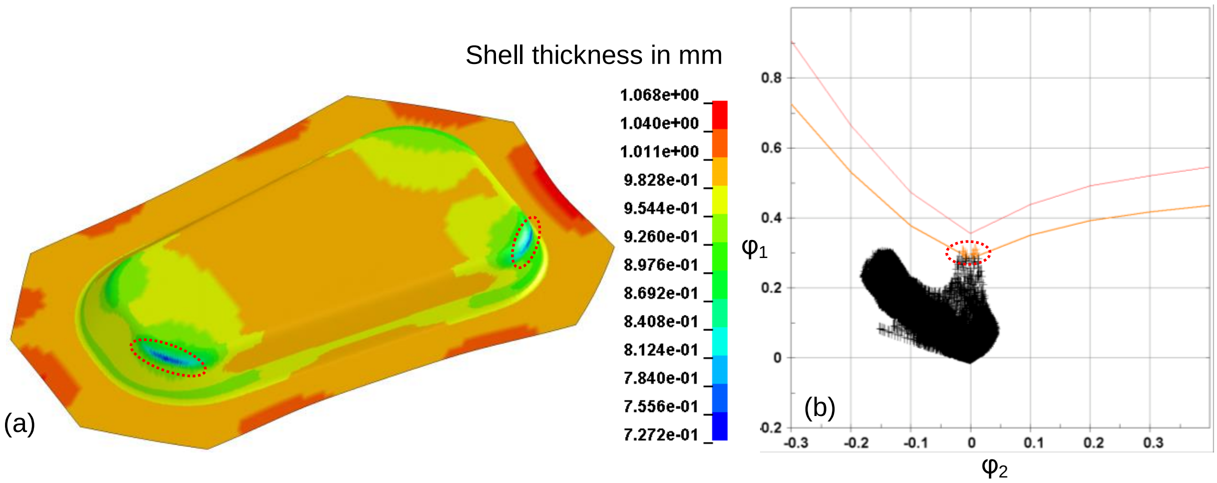

Fig. 5: Simulation results gained by modelling blank holder as rigid;
(a) thickness distribution, (b) forming limit diagram

Simulation results taking into account active tool components as rigid showed an increased tendency for crack arise due to high material thinning as well as wrinkles of second order in certain part areas. There was no possibility to optimise the blank holder force or friction coefficient any further in order to achieve a bigger deep drawing depth without occurred cracks considering small tendency for wrinkle formation.

4.3 FEM-Model for elastic blank holder

In order to increase the deep drawing depth, considering the requirements for part surface quality (wrinkles, cracks, etc.), the finite element simulation with an elastic blank holder was carried out. Use of elastic blank holder allows to locally apply different surface pressures on the part. This can be realized by varying the blank holder stiffness by using appropriate order and type of the supporting elements. The blank holder consists of one cover plate in this case which is supported by numerous elastic elements. In order to describe the elastic behavior of the tool, blank holder plate and corresponding supporting elements were meshed with solid elements. For those tool parts one elastic material model *MAT_ELASTIC was assigned.
The tool parts were modelled by using CATIA V5 software. For modelling the deep drawing process the softwares DynaForm 5.8.1, LS Prepost 4.1 and Texteditor Notepad++ were used. DynaForm was used for positioning the tool parts as well as for defining forces and tool motions. Appropriate contacts between tool surfaces and part were defined by using the software LS Prepost. Due to numerous simulative optimisations, small changes regarding friction coefficient, blank holder force and other influencing parameters were conducted by using Texteditor Notepad++. The tool surfaces of the punch, die and adapter plate were meshed with shell elements (Belytschko-Tsay-Shell, ELFORM 2). Afterwards, one material model for rigid body *MAT_RIGID was assigned for the mentioned tool parts.
For punch and die contact *FORMING_ONE_WAY_SURFACE_TO_SURFACE was defined. Contact type *AUTOMATIC_SURFACE_TO_SURFACE was used to describe the contact between blank holder plate with the supporting elements as well as between adapter plate and supporting elements. Between blank holder plate and part, the contact type *AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE was defined. Main aim of defined FE-Model was to analyze influence of blank holder elasticity on material draw-in and accurate prediction of the achievable part height without cracks as well as wrinkle formation. Also load optimisation of the blank holder structure aiming to reduction of wrinkles of second order was carried out here. The motion of the die was disabled during the simulation. In order to form the required part shape, the motion function was applied to the punch. The punch motion was defined with one sinus function. Within the short time a maximal speed of 2.000 mm/s was achieved. Shortly before the maximal deep drawing

depth the punch speed was sinusoidally reduced to 0 mm/s. Fig. 6 shows steps for FE modelling and simulation of deep drawing process with the elastic blank holder.

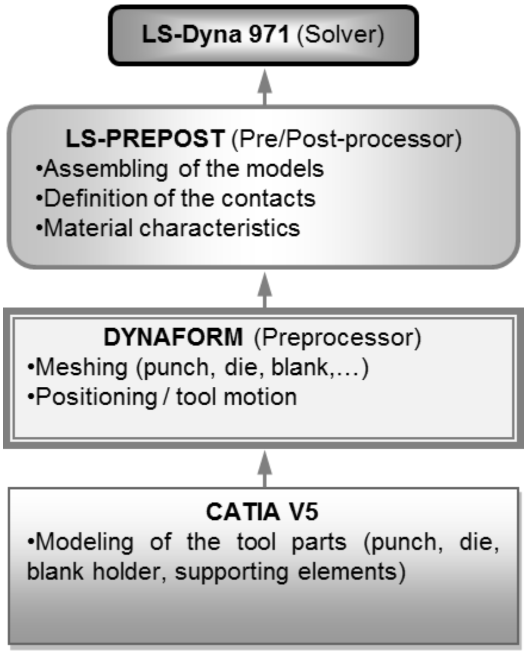

Fig. 6: Steps for FE modelling and simulation

4.4 Simulation results considering elastic blank holder structure

Numerous simulations of the deep drawing process with the elastic blank holder structure were carried out. Blank holder was load optimised by means of arrangement and appropriate elasticity of the supporting elements. The main aim of these simulations was to optimise blank holder structure which allows appropriate blank holder plate deformation depending on caused sheet metal thickening during deep drawing process. Results of this optimisation should increase achievable deep drawing depth, but take into account the reduced tendency for wrinkle formation as well. In Fig. 7a, displacement of the blank holder plate in z direction is shown. Applied blank holder force was 1000 kN and deep drawing depth was set to 70 mm. Thus, it can be seen that the blank holder plate is variable deformed although one point press cushion system is considered during the simulation. This effect can be explained due to variable sheet thickening which occurs during deep drawing process as well as corresponding deformation of the blank holder plate. Fig. 7b shows a forming limit diagram of the formed part. In this case it was possible to achieve a deep drawing depth of 70 mm without risk of crack development.

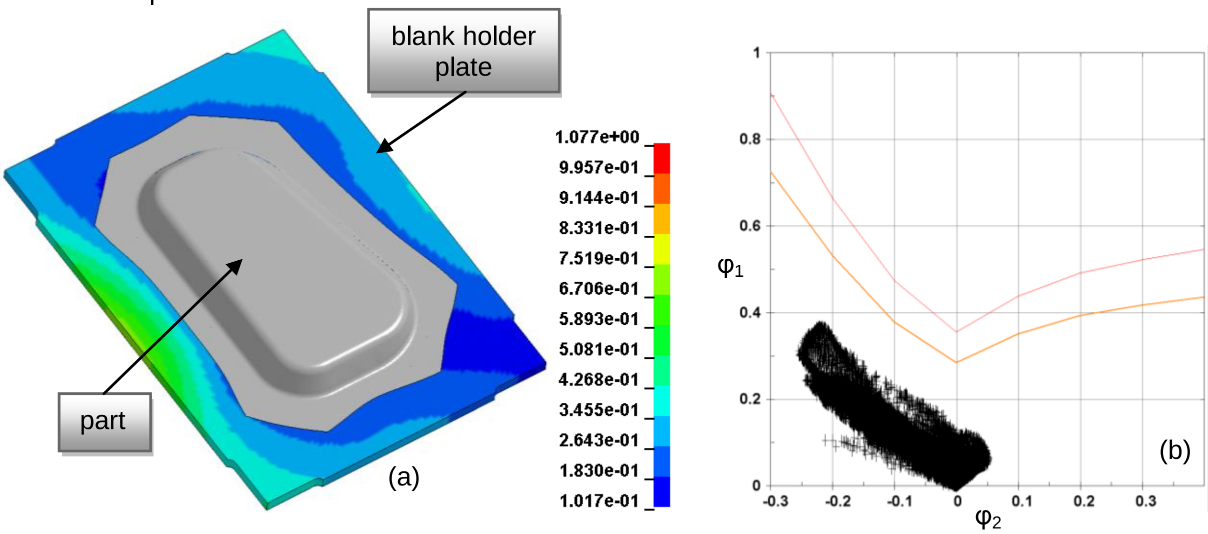

Fig. 7: Simulation results by using the elastic blank holder model; (a) Displacement of the blank holder plate in z direction, (b) Forming limit diagram (FLD)

Compressive stresses in the flange area of the part will cause corresponding sheet thickening. Pressure peaks will appear in the contact area between the part and tool surfaces where extreme thickening has occurred before. Mentioned pressure peaks will stop material draw-in and therefore the tendency for cracks development will be increased. The tendency for wrinkle development increases as well.

The purpose of the load optimised blank holder is to adapt the blank holder plate deformation regarding changeable sheet thicknesses which occurred in flange area of the part as well as to adjust the material draw-in regarding part geometry. In area of expected high sheet thickening, blank holder structure has to be modelled softer.

Fig. 8 shows influence of the blank holder stiffness on material draw-in. Simulations were carried out by applying a blank holder force of 1000 kN and deep drawing depth of 70 mm. Fig. 8a portrays in detail material draw-in considering uniform blank holder stiffness. In this case the supporting elements with the same mechanical properties and same consisting features were positioned side to side surrounding the deep drawing outline of the tool. Material draw-in was measured by using the LS Prepost software at the four identified critical areas. Simulation results showed that the material draw-in from left and right side (perpendicular to the drawing outline) is approximately balanced.

Results showed an increased tendency for wrinkle and crack development as well (especially at the part sides with the corresponding material draw-in values of 16,45 mm and 23 mm). In order to increase deep drawing depth in a robust manner, optimisation of the supporting structure of the blank holder plate is done. In the part area indicating simulation results showed extremely high sheet thinning, supporting structure was modelled softer allowing a higher deflection of the blank holder plate.

This was realized by using supporting elements with different Young's modulus of elasticity as well as appropriate order. Fig. 8b shows material draw-in assuming optimised blank holder stiffness. In the critical areas of the part, material draw-in is significantly increased. At the upper left side of the part, the material draw-in is increased by 6,97 mm, while at the lower right side material draw-in is increased by 5,33 mm. From the corresponding opposite sides of the part, the material draw-in is reduced, but for the amount which is lower than proportional. Due to that, the risk of cracks was reduced significantly.

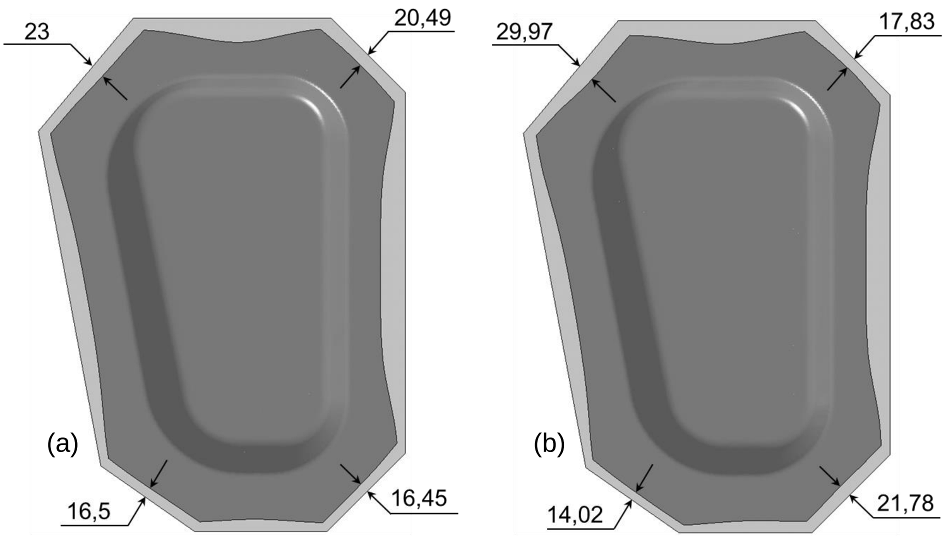

Fig. 8: Material draw-in; (a) uniform blank holder stiffness, (b) optimised blank holder stiffness

For optimised blank holder stiffness regarding crack development, wrinkle formation process was analysed as well (Fig. 9). In the most sensitive area of the part regarding wrinkle development, two finite elements were selected (Fig. 9a). For these elements dependency of minimum principal stress (compressive stress) and deep drawing depth is analysed (Fig. 9b). It can be seen that the compressive stress has achieved his maximum value at the deep drawing depth of approximately 44 mm for both finite elements.

At this defined point of the diagram (Fig. 9b) minimum principal stress starts to reduce its value, and further its amount does not tend to the value 0. After achieving the maximum, its value is changed cyclically. Considering the obtained results, the deep drawing depth in this case is significantly increased when compared to deep drawing with the "rigid" blank holder which has not been optimised. Also, the tendency to wrinkle development is reduced noticeably.

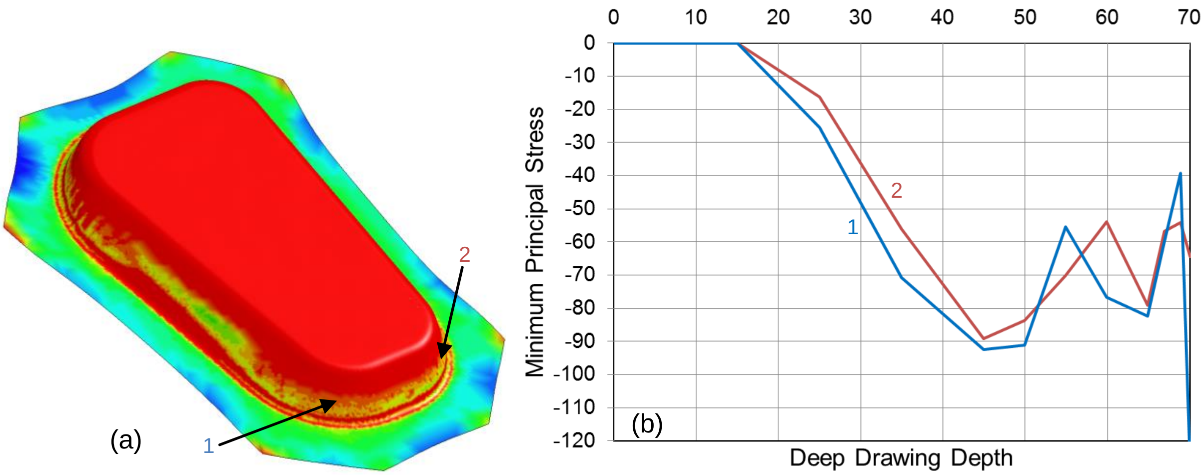

Fig. 9: Analysis of compressive stresses distribution; (a) selected elements at the formed part shape, (b) relationship between minimum principal stress and deep drawing depth

5 Experimental work

For the experimental determination of the wrinkle height occurred during the deep drawing process, selected parts were digitized by using the optical measurement system GOM ATOS. In order to avoid the reflection during the measurement process, the considered parts were treated with a matt white colour. The thickness of the layer of colour had to be extremely thin to aim at reducing the measurement failure.

After the parts have been digitized successfully, the obtained results were converted into a STL (Stereolitography) file. Afterwards, these results of the mentioned file were compared with the reference geometry of the part. For this purpose GOM Inspect software was used. First, the measurement results as well as the reference geometry of the part were imported into the mentioned software code. The next step was to determine the wrinkle height as precise as possible. Fig. 10 shows differences regarding part shape deviations. Deep drawing depth of the parts was 60 mm. In the first case (Fig. 10a), the part was deep drawn with a blank holder force of 900 kN. Experimental results showed that higher part shape deviations occurred. These deviations consist of the wrinkles as well as spring back (sidewall curl and angle change). The highest measured deviation was +2.42 mm, and at this area of the part, wrinkle of the second order is visible. The other deviations in the sidewall area of the part are a result of the elastic recovery or spring back after the part is relieved during deep drawing process. In the second case (Fig. 10b), the part is deep drawn by applying a blank holder force of 1050 kN. Measurement results showed that the highest deviation in analysed part area is +1.60 mm. There was no visible wrinkle development at this part. Occurred deviations at this part can be described as a spring back. This means, after the part is removed from the die cavity, remaining elastic stresses caused the change of part shape. The shape deviations in sidewall area near to part flange have occurred as result from angle change and sidewall curl. When compared to measurement results in Fig. 10a, it can be seen that part shape deviations have been reduced in general for a part which was deep drawn by applying higher blank holder force. In this experiment the blank holder was modelled having a uniform stiffness.

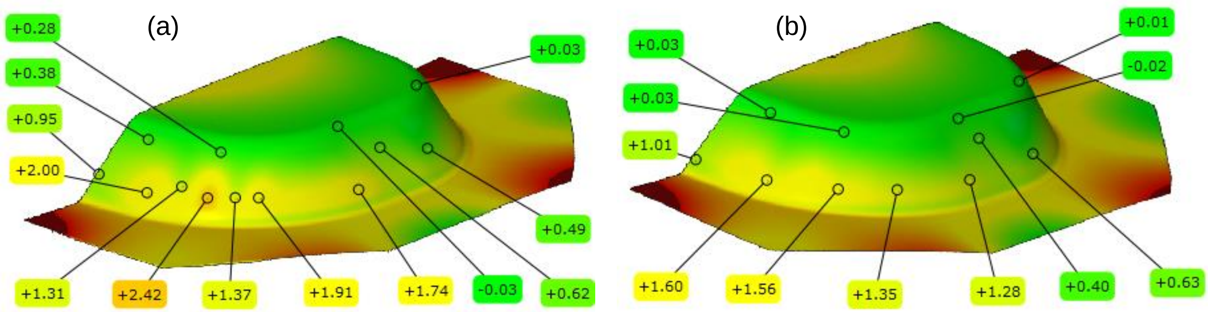

Fig. 10: Comparison of the wrinkle height; (a) deep drawing with the blank holder force of 900 kN, (b) applied blank holder force of 1050 kN

Applying the higher blank holder force (>1050 kN) led to the development of cracks considering the uniform blank holder stiffness in order to reduce part shape deflections further.
Lower blank holder force resulted in very high wrinkles. Regarding the achieved simulation results for deep drawing depth of 70 mm, the appropriate blank holder is assembled. The blank holder consists of the blank holder plate and corresponding supporting elements with the appropriate elasticity modules and arrangement (in regard to simulation results presented in Fig. 8b and Fig. 9). Experimental results achieve drawing depth of 70 mm without cracks as well. Fig. 11 depicts experimental results for a part which was deep drawn with the optimised blank holder structure. The highest shape deviation here amounts around + 1.35 mm. No visible wrinkles in the part sidewall area were detected. The deviations occurred in the part sidewall are a result of elastic recovery which occurs after the part is removed from the tool. When comparing the results obtained in this case with the evaluated results for parts which were deep drawn with the "rigid" blank holder, it can be seen that here the part shape deviations in general were significantly reduced.

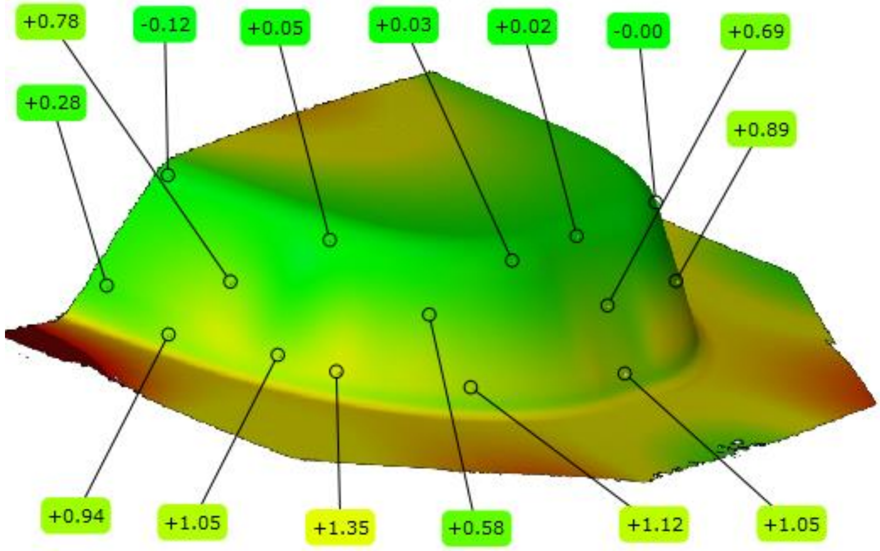

Fig. 11: Shape deviations for part deep drawn with the optimised blank holder stiffness (drawing depth is 70 mm; applied blank holder force ranges 1000 kN)

6 Conclusion

In this work, model of the blank holder was optimised. Taking a car fender shape as an example, investigation results showed that it is possible to increase deep drawing depth significantly when having the optimised blank holder stiffness. Maximal achievable deep drawing depth with the uniform blank holder stiffness without occurrence of cracks and wrinkles was 60 mm. Simulation results portrayed that the wrinkle initiation process has already started at the deep drawing depth of 17 mm when considering the uniform or "rigid" blank holder stiffness. It can be assumed that the wrinkle is completely formed at the deep drawing depth of 57 mm. In regard to results presented here, whole wrinkling process can be divided in four areas: 1st area is defined as safe area, 2nd area shows wrinkle initiation, 3rd area is growth of the wrinkle and 4th area is finishing of wrinkle formation process. With the optimised blank holder stiffness, the deep drawing depth with regard to satisfying quality of part shape was increased to 70 mm. Simulation results in this case showed that the wrinkle initiation process first starts at the drawing depth of 44 mm. After achieving maximal value at this depth, the compressive stress cyclically changes its value, but does not diminish entirely. Regarding these results it can be assumed that the wrinkle in the selected critical part area was initiated, but it was not formed considering unstable changes of minimum principal stress.
Due to elastic modelling of the blank holder it is possible to influence its deflection in areas where extreme sheet thickening occurs during deep drawing. The tool load optimisation is of great importance especially when it comes to forming of steels with high tensile strengths. When compared to derived experiment, the simulative results showed that it is feasible to predict wrinkle formation process as well as successfully optimising blank holder stiffness aiming at increasement of deep drawing depth. Results of this investigation showed that it is possible to increase drawing depth significantly when forming with the load optimised blank holder.

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