Process chain simulation for "Die-Less-Hydroforming" including Welding and Forming using "DynaWeld" and "LS-DYNA"

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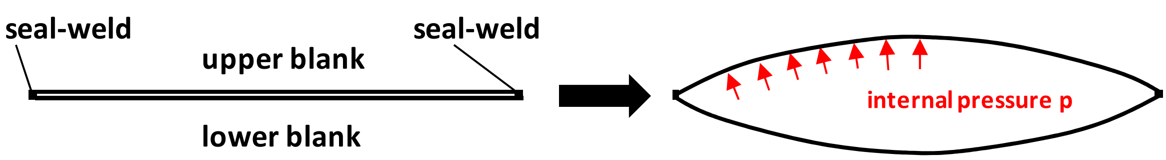
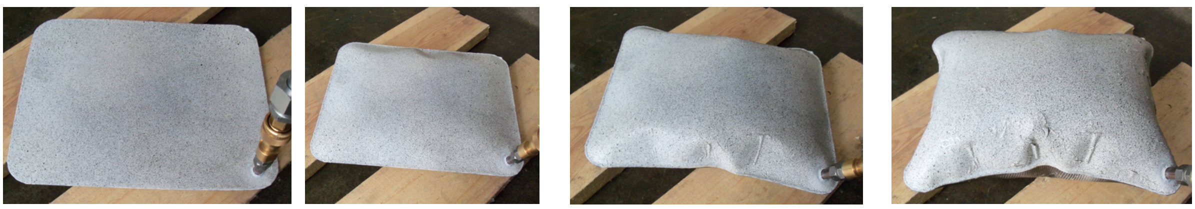
1 Introduction to "Die-Less-Hydroforming"

Within the scope of "Die-Less-Hydroforming", two or more thin metal blanks are joined at their edges by seal-welding. Thus, a two-dimensional flat "envelope" made of steel sheet results, that is formed into spatial structure through inflation of a medium (e.g. water) under continuous internal pressure increase. In comparison to conventional hydroforming-processes, no additional forming tool like a die or mould is used, leading to special phenomena like wrinkling or buckling during the forming process. The shape of the resulting 3D-structure is mainly controlled by the initial geometry of the blank and the forming internal pressure (see Fig.1:).
Actually, many users from different fields of application use "Die-Less-Hydroforming" for creating objects, sometimes also using synonyms like inflating metal as generic term or own nomenclature like "Blown Metal™"[1], "Freie Innendruck Umformung (FIDU)" (engl.: internal-pressure free forming) [2] or others for this forming technology. The fields of application include artwork (e.g. metal sculptures [3], [4]), functional design (e.g. furniture [5]), prototypical applications (e.g. [6]), state-of-the-art-industrial application (e.g. pillow-plates for vessels). As well as there is academic research undertaken (e.g. bearing structures [7]). Furthermore, mainly due to the comparatively simple equipment required, many hobbyists use this technology for creating objects for a wide range of application and present their work via the internet, where also some "crazy" applications of hobbyists can be found.
Although, "Die-Less-Hydroforming" is presently very up to date, presumably the first documented academic investigations on this special forming technology were already performed by Rawlings [8] in the 1960s. Further academic research was also performed inter alia by Greiner [9] or Kleiner et al. [10] in the following years. Rawlings already has recognized one of the major advantages of "Die-Less-Hydroforming": one-of-a-kind-manufacturing in combination with big sample dimensions, making this forming technology very interesting for structural building applications. Perhaps, today's revival of "Die-Less-Hydroforming" results from the technical progress and the good availability of CNC-cutting and welding technologies in recent years, providing the basic equipment required and facilitating the manufacture of almost every initial blank geometry now.



(a) principal scheme



(b) practical test with a double-layered thin stainless steel blank (1.4301) transforming to a pillow-like structure by inflating, here painted with a speckle-pattern for Digital Image Correlation (DIC)-measurement [11]

Fig.1: "Die-Less-Hydroforming"

2 Welding of seal-welds as the most challenging step of the manufacturing process of "Die-Less-Hydroforming"-objects and also as a motivation for the FE-process chain simulation

When looking to the manufacturing of an arbitrary "Die-Less-Hydroforming"-object in detail, it consists of four main steps: Cutting of the blanks, implementation of the valve, seal-welding at the edges of the blanks and finally inflating. Whereas nowadays cutting of the blanks (e.g. by laser-, plasma- or waterjet-cutting as well as manual handmade-cutting as the simplest way) is state-of-the-art, welding of the seal-weld at the edges is more technically challenging. On the one hand, the seal-welds should be filigree as possible to act as a yielding-line, where, on the other hand, the seal-welds have to stay seal until the end of the desired forming state. The required weld quality, i.e. especially the state of forming that should be achieved, naturally depends on the kind of object and its use. For art objects, a lower welding quality maybe is acceptable (and even bursting during inflation is sometimes intended by some artists), whereas for technical objects with a desired high forming state a high welding quality is necessary.

Thus, a special benchmark test for "Die-Less-Hydroforming"-weld-seams was developed by Steidl, Metzger and Ummenhofer (see [12]). This test allows the easy, fast and cost-saving investigation and assessment of the general performance, load-displacement-behavior and suitability of a specific type of seal-weld using small samples in a combined bending-tension test procedure.

When looking to existing "Die-Less-Hydroforming"-objects, one can mostly find two types of weld-seams: overlap welds and face welds. The choice of the welding process corresponds directly to the type of weld-seam. An overview of different possibilities can be found in [11]. Thereby, the automation level of the weld-process itself reaches from manual operated welding to fully automated robotic welding influencing the quality of the seal-weld and its performance during inflation.

Many different metal sheet base materials can be used for the manufacturing of double- or multi-layered "Die-Less-Hydroforming"-blanks located in the thickness range from 0.5 mm to 4 mm. The right selection of the base material and the specific alloy as well as the optional weld filler material depends on the current application.

In this paper, we focus on double-layered stainless steel blanks that are joined by face welds executed by arc welding (in detail: TIG-Welding without filler material, weld process no.: 142).

Due to low thickness of the thin metal sheets, a fixation of the two blanks during welding is essential to avoid intense welding distortions. On the other hand, the fixations and thereby the reduction of the welding distortions maybe increase the residual welding stresses. It is now assumed that the residual welding stresses or welding distortions resulting from seal-welding of the blanks have a strong and very sensitive influence on the "Die-Less-Hydroforming"-process with regard to instabilities like buckling and wrinkling in particular due to the small sheet thickness. Especially this context motivates the current contribution.

A FEM-simulation of this special forming process with "LS-DYNA" was already introduced by the authors inter alia in [13]. Furthermore, a thermo-structural-mechanical welding simulation of the assembly process of the blanks was developed using the software "DynaWeld" and the related solver "LS-DYNA"; see [11]. Both steps are now connected resulting in a process chain simulation as follows.

3 Process chain Simulation of "Die-Less-Hydroforming" including welding and forming

3.1 Initial situation and combined FE-modeling scheme for welding and forming

For reasons of a better understanding, some modeling details (taken from [11], [13], [14]) are summarized first.

From now on, the modeling procedure is only explained for double-layered "Die-Less-Hydroforming"-blanks, of course, the explained modeling strategy of Fig.2: can also be used for the creating of a simulation model with multi-layered blanks.

At the beginning, the flat 2D-blank geometry of any "Die-Less-Hydroforming"-object exists in form of an arbitrary CAD-data-file (e.g. the edge contour is drawn by a polygonal-line or curve). Based on this CAD-drawing, the simulation can be set up by exporting this CAD-data via an export format file (e.g. iges, sat) to the preprocessor. Whereas for the thermo-structural-mechanical coupled welding simulation, an implicit "LS-DYNA" analysis is performed, afterwards the forming simulation is carried out with the explicit solver using time-scaling and mass-scaling (as it is also often used for the simulation of conventional forming processes). For this reason, the meshing of the blanks needs special attention. Implicit welding simulations normally use individual meshes regarding mesh sizes.

Especially the weld zone and the heat affected zone (HAZ-zone) show a more fine mesh compared to other regions, mainly to save computation time. For the subsequent explicit forming simulation, the time step size is directly determined by the critical time step size according to the Courant–Friedrichs–Lewy criterion, where the smallest element size is a direct parameter. So consequently, for the process simulation of “Die-Less-Hydroforming”, we also use a size-grade mesh, that will save immense computation time during the implicit welding simulation. In doing so, this will be advantageous especially for big dimension samples.
Meshing of the blanks can be performed using “LS-PrePost”, perhaps due to the historical function of “LS-DYNA” as an explicit solver, creating size-graded meshes with “LS-PrePost” is a little bit uncomfortable. Thus, for this special meshing step other preprocessors might be more powerful.
When looking at Fig.2:, the combined modeling of a double-layered “Die-Less-Hydroforming”-blank for the modeling of the weld seam for a welding simulation (according to [11]) as well as for a forming-only simulation (according to [13], [14]) is presented.
Finally, starting with the already meshed single blank, from which the meshed double-layered blank has to be created, which could be easily done by duplicating the meshed single blank with a short gap "d". This short gap "d" is necessary to avoid numerical instabilities (e.g. due to initial contact between both blanks).
Furthermore, a solution for joining the two blanks is needed, that can both used in welding as well as forming simulations. Subsequently, all edge nodes of both blanks are transferred into positive or negative normal direction with a distance of t/2+d/2. In doing that, respectively an edge node derived from the upper and the lower blank are now located on the same position. Consequently, the edge can now be “seal-welded” in the FE-model by merging duplicated nodes. This procedure of creating the seal-weld is the simplest solution and leading to very good simulation results. In addition, a more detailed modeling of the seal-weld, for example by finer meshing or even by using solid elements in the weld zone, is possible. Finally, modeling of the weld-seam should match its real load-displacement-performance which is fulfilled for the current used model of Fig.2: (c.f. [12]).
Additional fixation and gripping equipment such as aluminum plates which are necessary during welding have to be modeled separately (e.g. by solid elements).

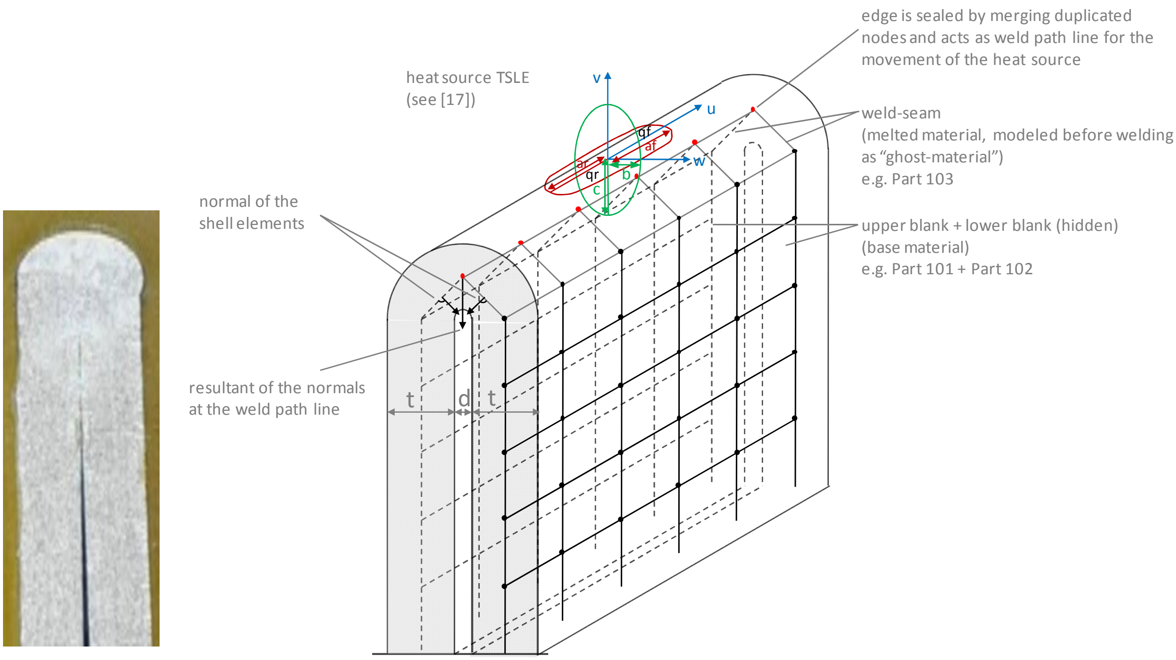


Fig.2: Modeling scheme of a double-layered “Die-Less-Hydroforming” blank (taken from [11] and supplemented) including heat source for welding and a corresponding exemplified macrosection of the face weld, however, additional fixation equipment is not illustrated

3.2 Welding simulation for “Die-Less-Hydroforming”-blanks: Some details of modeling and simulation using “DynaWeld” and “LS-DYNA”

With the modeling scheme according to Fig.2:, a thermo-structural-mechanical welding simulation using “DynaWeld” as a preprocessor and “LS-DYNA” as an implicit solver can be set up. The detailed procedure is presented in [11], further details especially regarding “DynaWeld” (e.g. rules of

denotation and numbering the different parts) are documented in special manuals [16] or [17]. Some main specific details for the welding simulation of “Die-Less-Hydroforming” blanks are now given. Starting with taking the meshed double-layered blanks (base material and weld-seam), optional some fixation equipment, the weld path lines (in terms of node sets) and the material data as source data in the form of separate ***KEYWORD**-files, all further preprocessing is performed using “DynaWeld” via a GUI-interface in combination with a spreadsheet called “Processplan”. By means of the “Processplan” spreadsheet, all necessary simulation parameters such as general simulation parameters, parts definition, boundary conditions, thermal and mechanical contact conditions and so on as well as all welding process parameters can be defined. Especially the input setting of the latter, the welding parameters, is strongly leant on a “Welding Procedure Specification (WPS)” used in practical manufacturing, and making it easy to input these parameters.
Of course, all material values have to be put in temperature-dependent for the welding simulation. For the current simulations, these values for the blanks as well as for the fixation equipment were provided by DynaWeld GmbH & Co. KG.
A specific heat source (called TSLE, c.f. Fig.2:, for further details see [17]) is used, for which the movement is only controlled by a weld path consisting of element nodes. The direction of the weld source is determined by the resultant of the element normal from both element rows forming the continuous weld path line.
At the end of preprocessing, the “LS-DYNA” input files for the welding simulations are automatically generated via the GUI-interface of “DynaWeld”, and the thermo-structural mechanical welding simulation can be performed.

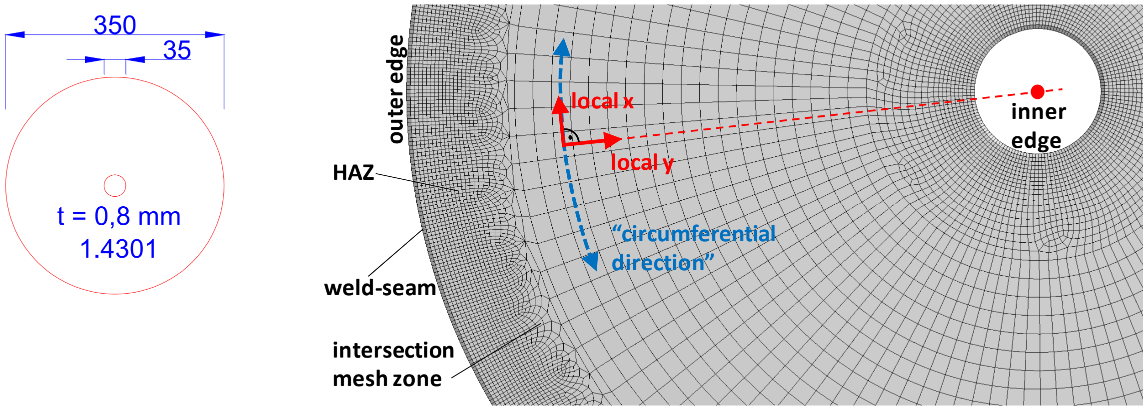
3.3 Forming simulation of “Die-Less-Hydroforming”-objects using the DYNAIN-file to include welding distortions and residual stress at the initial state of the simulation

The forming simulation of the inflating process of a double-layered “Die-Less-Hydroforming”-blank was already introduced by the authors in [13], [14] as well as [15] and is shortly summarized as follows. By the way, this simulation model can also be used for multi-layered-“Die-Less-Hydroforming”-blanks as well as for the inflation of seal-welded 3D-hollow bodies (e.g. for the inflation of a cube transforming partly to a sphere according to experimental investigations in [9]).
Of course, the explicit forming simulation is non-linear regarding geometry (large deformation), material (plastic hardening) and the structure (e.g. self-contact of wrinkles). As already mentioned, time-scaling and mass-scaling is used. First of all, 4-node Belytschko-Tsay shell elements are chosen for the discretization of the blanks, whereas reduced integration using “LS-DYNA Hourglass-Control” is selected. For the material behavior ***MAT_PIECEWISE_LINEAR_PLASTICITY** (***MAT24**) is used, with either at least a bi-linear or a multi-linear flow curve, which values are determined from an uniaxial tension test. Modeling of contact (e.g. for the special case of self-contact in wrinkles) is realized by ***CONTACT_AUTOMATIC_SINGLE_SURFACE**.
Particular attention should be given to the load model for internal pressure. There are different possibilities. Applying a simple distributed load model by using ***LOAD_SEGMENT** or ***LOAD_SEGMENT_SET** is state-of-the-art for conventional hydroforming (c.f. [18]), and also works for “Die-Less-Hydroforming”-forming simulations. Somewhat unorthodox, but very interesting with regard to the results, is our special solution when using an existing advanced airbag-load-model of “LS-DYNA”, called ***AIRBAG_LINEAR_FLUID**, which is recommended for hydroforming simulations in [19]. Within this keyword, one has the choice to input the load through a mass input flow curve versus time (dM/dt) via ***DEFINE_CURVE**, from which the resulting internal pressure is calculated via a physical relation including bulk modulus, volume and pressure. Otherwise, the load can be applied directly by defining an internal pressure versus time curve. When using the airbag model, it is mandatory that the doubled-layered “Die-Less-Hydroforming”-blank is completely sealed regarding the FE-mesh at the edges to get a closed control volume. In addition, the normals of all elements of both blanks have to be directed from outside to inside in addition.
Now for the current process chain simulation, this modeling and simulation strategy can be used identically, however, instead of the undistorted and “perfect” double-layered “Die-Less-Hydroforming”-blank, the “imperfect” blank resulting from the thermo-structural-mechanical welding simulation is used, exported via a DYNAIN-File. This means that welding distortions as well as residual stresses are available at the initial state of the forming simulation. Therefore, the DYNAIN-File has to include specific Keywords such as ***ELEMENT_SHELL_THICKNESS**, ***INITIAL_STRESS_SHELL**, ***INITIAL_STRAIN_SHELL**, etc., however, this is user-friendly automatically controlled by the output of “DynaWeld” respectively “LS-DYNA”.

4 Some results of the process chain simulation in extracts

For showing the operation mode of the process chain simulation and its benefits, a special “Die-Less-Hydroforming”-sample (a circular disc with an inner hole at the center) as well as the corresponding welding simulation results from [11] are taken.

The special blank geometry (looking like a circular ring) and a part of its mesh as well as the corresponding local element coordinate system is given in Fig.3:. The blanks are individually meshed centrically from the center with 4-Node-Elements, using a finer mesh at the weld zone and HAZ, which necessitates to have some intersection mesh zones between the zones with different mesh size. For the meshed areas with the centrically oriented regular mesh the local element coordinate system is always oriented with y-axis in direction to the center point of the circular ring sample. Since the local x-axis is automatically perpendicular to the local y-axis per definition, allowing us to obtain “circumferential values” (e.g. stress) by evaluating the local element values of the local x-axis as follows. Please notice that in the intersection mesh zones many non-orientated and distorted elements as well as some triangle elements are necessary leading to a diverse orientation of the local coordinate system and consequently to disarranged plotting colors there.



(a) blank geometry [mm] (b) meshing details and orientation of local element coordinate system

Fig.3: Details of the circular ring “Die-Less-Hydroforming”-sample (taken from [11] and supplemented)

Using “DynaWeld” for preprocessing and “LS-DYNA” as solver, the thermo-structural-mechanical welding simulation was performed including first the welding of the outer edge, second the welding of the inner edge and finally the cooling-down phase like in reality. Here, the manual hand welding performed in reality was considered by subdividing the welding of the outer and inner edge to some weld-lines with welding parameters lightly varying. Two main model configurations for the welding simulation (without and with fixation) of the double-layered circular ring blank geometry as well as some corresponding results are given in Fig.4:.

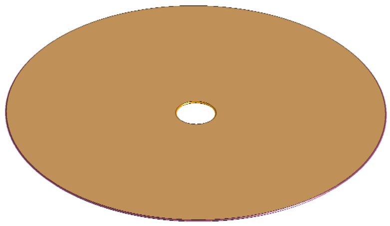
When looking especially to the simulation results in terms of welding distortions normal to surface after cooling-down to ambient temperature, the effect of fixation can be obviously investigated. Whereas the model configuration without fixation results in strong and very inhomogeneous welding distortions with a maximum displacement amplitude of 16.0 mm (c.f. Fig.4: (c)), the model configuration with fixation in terms of aluminum plates on both sides have only small, smooth and homogenous welding distortions with a maximum displacement amplitude of 6.1 mm (c.f. Fig.4: (d)).

These simulation results concerning welding distortions match the results of some real welding samples very good in a quantitative as well as in a qualitative way (c.f. Fig.4: (e) and Fig.4: (f)).

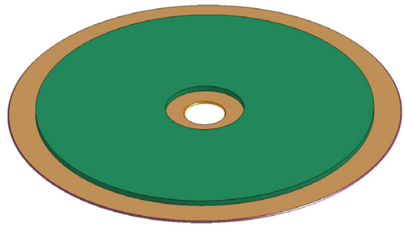
Now, with this double-layered circular ring blank geometry, a forming simulation with two different configurations is performed:

Configuration 1:	“Perfect” double-layered “Die-Less-Hydroforming”-blank <u>without</u> previous welding simulation
Configuration 2:	“Imperfect” double-layered “Die-Less-Hydroforming”-blank <u>with</u> previous welding simulation using fixation by aluminum plates which results in realistic initial welding distortions, and also includes initial residual welding stress according to Fig.5: (b)

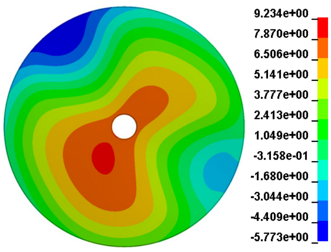
Of course, the same load curve (in terms of a mass input flow curve versus time) and the same mesh for both configurations is used making it possible to compare them directly state-by-state.



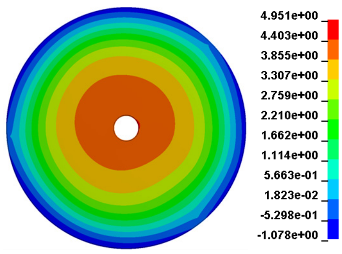
(a) model configuration without fixation



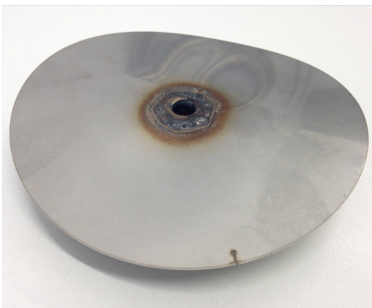
(b) model configuration with fixation in terms of aluminum plates on both sides



(c) welding distortion [mm] normal to surface after cooling-down to ambient temperature for the model configuration shown in (a)



(d) welding distortion [mm] normal to surface after cooling-down to ambient temperature for the model configuration shown in (b)



(e) welding distortion for a circular test welding in the center of a circular blank (here: d=110 mm, t=0,8 mm) made of 1.4301 without any fixation

f) welding distortion of the double-layered "Die-Less-Hydroforming"-blank according to Fig.3: (maximum displacement amplitude normal to surface in the range between approx. 5 up to 6 mm), in this case admittedly welded with fixation by chipboard plates

Fig.4: Results of the thermo-structural-mechanical welding simulation of a circular ring sample (taken from [11])

For further studies, the local element true stress in "circumferential direction" and the development of buckling at the outer edge in terms of in-plane-displacement for different states of inflation is given in Fig.5: respectively Fig.6: for Configuration 1 as well as for Configuration 2.

Considering the forming simulation of Configuration 1 with "perfect" double-layered blank geometry, we can recognize that at the outer edge of the circular ring a circular compressive force in terms of compressive stress develops during the inflation process. This compressive stresses increase during the progressing inflation simulation leading to circumferential smaller buckles at the outer edge if the critical buckling stress is reached. When still continuing the inflation process, further local buckling at the outer edge occurs transforming locally into some huge wrinkles with self-contact.

When looking to the hole with the inner circular edge, a circular tension force in terms of tension stress develops during the inflation process. This tension force increases during inflation which results in a huge centric enlargement of the inner hole. Under tension stress of course, no buckling occurs at the inner circular edge, but a fracture in the seal-weld might occur in reality when reaching the critical tension stress or rather the critical strain (c.f. Fig.5: (a) and Fig.6: (a)).

The question is why is it so interesting to make a process chain simulation including welding and forming? In the next step, taking Configuration 2, the forming simulation is performed again using the resulting double-layered blank from the welding simulation which includes the welding distortions and

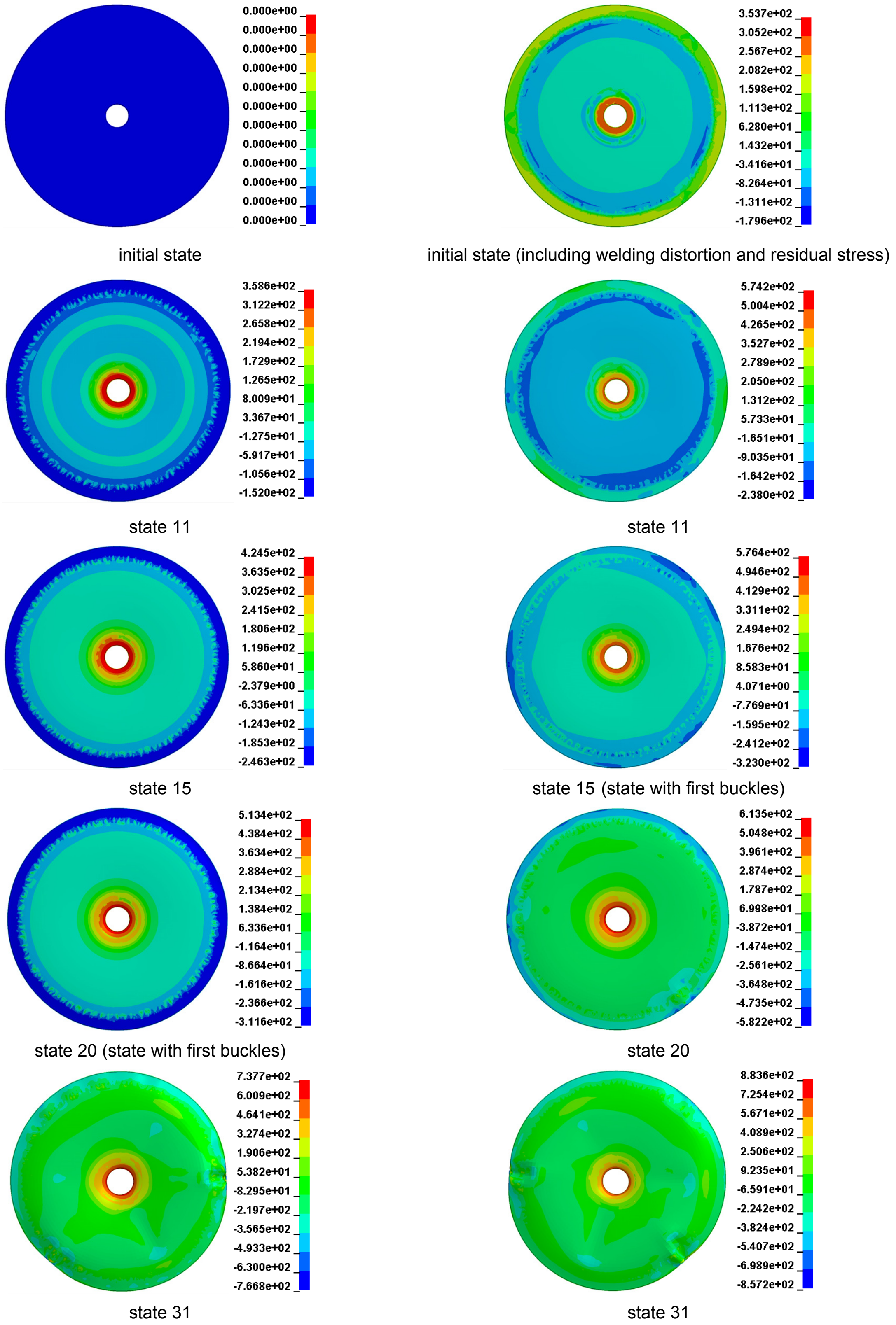
residual stresses at initial state. When welding the weld-seams at the outer and inner edge, first the weld seams expand and afterwards they shrink during cooling, which leads in combination with the fixation equipment to the characteristic distribution of the welding residual stress shown in Fig.5: (b) in the initial state. From the outer to the inner edge "circular areas" in terms of "circumferential residual stress" remaining from welding simulation, which are now overlain by the resulting stresses from the inflation process.
At the inner hole, the existing high welding residual tension stress is overlain by the tension stress resulting from the forming simulation, which might lead to an earlier fracture of the seal-weld at the inner hole. At the outer circular edge of the sample, the small circular area of low welding residual tension stress have to be first compensated by the compressive stress establishing and increasing during inflation. However a very huge adjacent circular area of welding residual compressive stress dominates the initial state of Configuration 2. This means in detail, when comparing the simulation results of Configuration 1 and Configuration 2 state-by-state, you can observe, that the first buckling occurs earlier in Configuration 2 compared to Configuration 1. Since the same load curve is used in both simulations, we conclude that this effect of earlier buckling is caused by the welding distortions and welding residual stress included at the initial state of Configuration 2. Additionally, the state of the beginning of buckling in Configuration 1 can be clearly determined, whereas in Configuration 2 (perhaps due to the existing welding distortion and residual stresses) the beginning of buckling can apparently not be determined and seems to be distributed over a few states. The kind of buckling also diversifies between Configuration 1 and Configuration 2. Nevertheless, the range of the critical compressive stress when buckling occurs is similar in both configurations (c.f. Fig.6:).

5 Summary

A process chain simulation for "Die-Less-Hydroforming" including welding and forming using "DynaWeld" and "LS-DYNA" is developed. It can be used for double-layered as well as multi-layered "Die-Less-Hydroforming"-blanks with arbitrary geometry that are seal-welded by face welds using TIG-welding without filler. Generally, the process chain simulation can also be used for other types of seal-welds as well as other welding procedures (e.g. MAG-welding), perhaps necessitating to adapt the modeling scheme of Fig.2: especially in the weld-zone.
In the first step, the joining of the double-layered blanks is simulated with "DynaWeld" and "LS-DYNA" which means the welding process by a thermo-structural mechanical welding simulation. Subsequently, a forming simulation of the double-layered blanks is performed, whereby the essential information from the welding simulation (that means distortion, residual stresses, etc.) is transferred through a DYNAIN-file to the forming simulation.
The detailed procedure for the preprocessing, modeling and simulation and its backgrounds are described above.
Some first simulation results of a special "Die-Less-Hydroforming"-sample (looking like a circular ring made of austenitic stainless steel (1.4301)) are presented, showing the initial assumption that the welding process of the "Die-Less-Hydroforming" blanks having a direct influence on the forming process in terms of the formation of buckles and wrinkles,
Since the numerical model seems to work fine, further extensive experimental tests (especially with automatically welded samples) are necessary to verify and validate and maybe optimize the process chain simulation and its procedure.

6 Acknowledgment

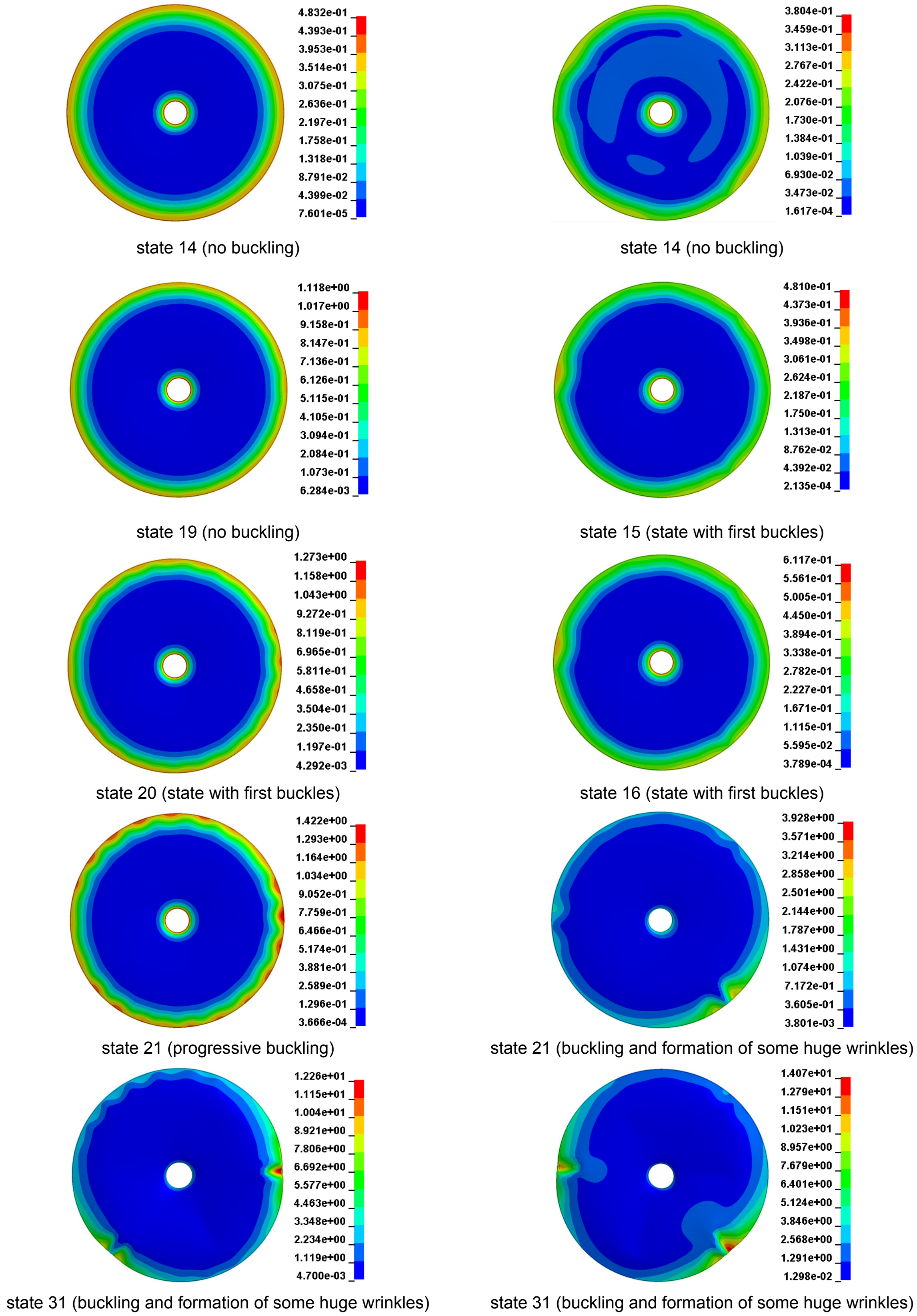
Special thanks go to DynaWeld GmbH & Co. KG for the free of charge disposal of the software "DynaWeld" including support.



(a) Configuration 1: without previous welding simulation

(b) Configuration 2: with previous welding simulation

Fig.5: Local element true stress [MPa] in "circumferential direction" of the circular ring sample (midplane integration point) for different states during the inflation



(a) Configuration 1: without previous welding simulation

(b) Configuration 2: with previous welding simulation

Fig.6: Visualization of the development of buckling at the outer edge of the samples in terms of in-plane-displacement [mm] for different states of inflation

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