Combined Working Media-Based Forming on a Pneumo-Mechanical High Speed Forming Machine

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Abstract

Quasi-static working media-based forming processes (WMF) permit the production of complex sheet metal parts with relatively little expense. The associated need for very high pressures and hence complex tools and machines for the production of fine geometrical details is often problematic. The use of high speed forming processes (HSF) can offer many benefits, including a reduced financial outlay on equipment and better part properties in this case. But these processes also have disadvantages, of course, such as if they are used for the production of complex large-surface parts. Consequently, a combination of both approaches would be ideal. This paper describes a new approach to combining high pressure sheet metal forming (HPF) and pneumo-mechanical HSF for the production of complex sheet metal parts.

Keywords

Pneumomechanical high speed forming, Working media-based process, Hydroforming

1 Working Media-based Forming Process

The working media-based forming processes (WMBP) are considered to be processes with a high innovation potential and are frequently used for the production of complex, multifunctional components in a large number of industrial fields. The WMBP include all processes in which a working medium (fluid) or a flexible non-compressible material is used in the processing of metallic semi-finished parts The fluid – mostly an oil in water emulsion – “transfers” the pressure to the semi-finished part, either directly or indirectly, and thus leads to the uniform forming. The pressure effect can be achieved through either internal or external working media sources, on a quasi-static or dynamic basis (Homberg, 2001 and Lange, 1993). The most important representatives of these technologies with their typical process characteristic are presented in Figure 1. The WMBP can essentially be divided into two groups with respect to the forming velocity:

- **Quasi-static working media-based forming process**
- **Dynamic working media-based forming process**

Classification of working media based forming process

Forming velocity	Quasi-static								Dynamic											
Working media	Flexible tools or working medium				Working medium				Accelerated rigid masses	Working medium with								Working energy		
										Force associated effect				Energy associated effect						
Semi-finished part	Blank		Tube		Blank		Tube		Blank	Blank		Tube		Blank		Tube		Blank		Tube
Working media contact directly=D indirekctly = I	D	I	D	I	D	I	D	I	D	D	I	D	I	D	I	D	I	D	I	I
Process examples	**HYDROMEC**	**Guerin Rubber Pad Forming**	**Variform**	**Tube expanding with water bag**	**High pressure sheet metal forming (HBF)**	**Verson Hydroforming**	**Tube Hydroforming**	**Hydroforming with membran**	**Petro-Forge Machins DYNAPAC**	**Hydropunch Mazukin**	**Hydropunch Chachin**	**Hydropunch Tominaga**	**Hydropunch with membran**	**Electrohydraulical Fomring (EHF)**	**EHF with Membran**	**Explosive forming**	**Explosive forming EHF with mebran**	**Electromagnetic forming with plunger**	**EMF**	**EMF**
Energy transmission media	Fluids, sand, rubber				Fluids				Rigid body	Fluids, sand, rubber				Fluids, sand, rubber				Air		
Pressure generation	Tool movement				Pressure intensifier				Mass movement	Plunger movement				Electrical discharge explosion				Magnetic fields		
Pressure duration	t > 10s				t> 10 s				10e-3<t<10e-1s	10e-4<t<10e-3s				t<10e-5s				t<10-5s		
Maximal pressure	p_{max}<100MPa				p_{max}<600MPa				p_{max}<1000MPa	p_{max}<300MPa				p_{max}<10.000MPa				p_{max}<500MPa		

Characteristic of working media based forming process

Figure 1*: Classification and characterization of working media-based forming processes (based on the work of Homberg, Beerwald, Lange and Mamutov)*

The use of working media-based forming processes (Fig.1) generally has numerous technical and economic advantages but also certain disadvantages. So the idea of combining several processes in order to create a new process is only logical. That is the way in which certain research work related to this topic was performed in the past (Mamutov, 2001).

One promising process chain, i.e. the combination of quasi-static/classic deep-drawing, has thus already been tested with electromagnetic high-speed forming in the PAK 343 and EMF-G3RD projects (Psyk, 2007 and Demir, 2014). The results of the projects have shown, on the one hand, that the existing forming limits of aluminum alloys and steel can be effectively extended by the correct sequence of forming processes. Additionally, in work by

Golovashchenko, a further promising approach is shown, improving the precision and complexity of components by combining the classical deep drawing process with an electrohydraulic high speed forming process, for more details see (Golovashchenko, 2011). This same combination method is also described in the work of Mamutov, where the so called pre-forming of the semi-finished parts is performed by deep drawing with a flexible working medium such as polyurethane. In this case, the calibration is performed by means of an electromagnetic forming process (Mamutov, 2001). Based on the research work conducted and the existing process characteristics of the WMF, it can be stated that, in the known variants, the combination partners differ significantly in terms of pressure generation, transmission and duration, as well as in terms of the process characteristics. There are only a few combinations where the same working medium and the same forming machine is used for the combined forming process. This paper thus presents a possible approach to combined working media-based forming processes where the advantages of quasi-static high pressure sheet metal forming and pneumo-mechanical high speed forming are combined on one and the same high speed forming machine (the so called Hydropunch machine), see Figure 2.

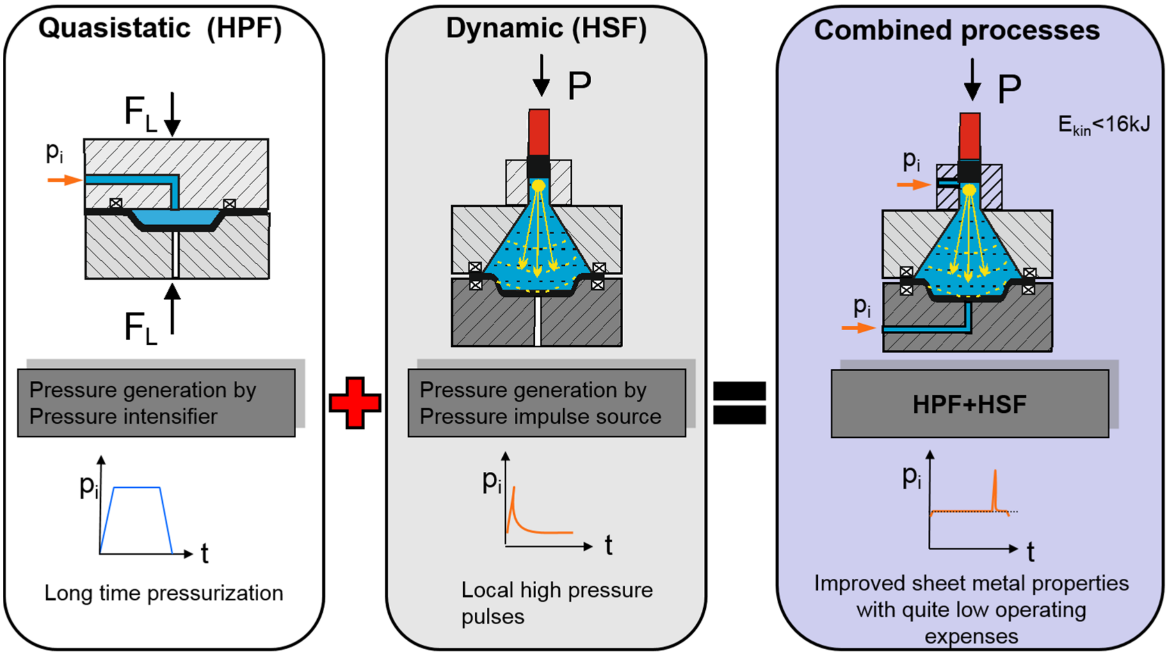

***Figure 2**: Concept for a combined working media forming process*

2 Potential Process Routes on the Combined Hydropunch Machine

The combination of quasi-static (pre)forming with high-speed forming processes like pneumo-mechanical HSF inside a single machine opens up new possibilities for process design. Hence it is possible to influence the strain distribution and preform geometry of the part in such a way as to positively affect the course and result of a subsequent high speed forming step. In this work, two different process strategies for combining quasi-static and dynamic forming process are presented, see Figure 3.

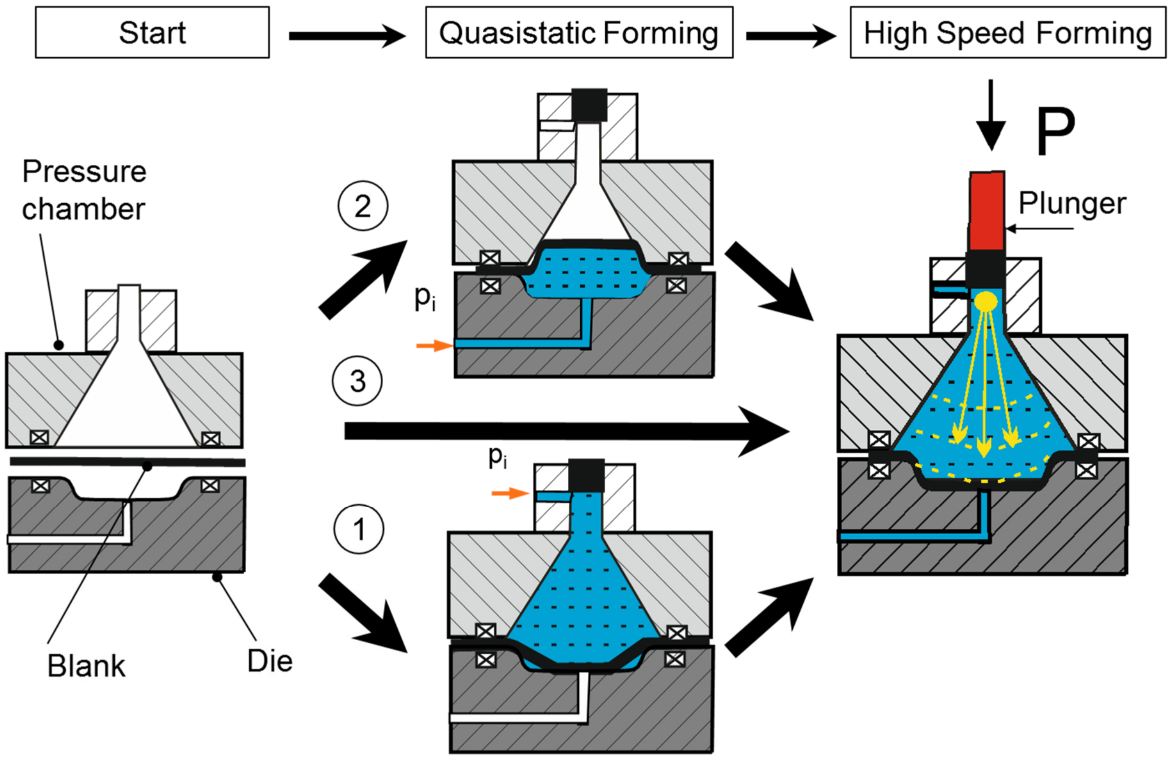

Figure 3*: Sequence of positive and negative preforming and dynamic calibration*

The first strategy (1) is characterized by preforming the semi-finished part quasi-statically in the positive forming direction (towards the forming die). The subsequent dynamic forming step is then used to calibrate the part. The deformation zone is quite small and is limited to the areas without contact between the sheet and die.

The second strategy (2) also employs quasi-static preforming. In contrast to this, the preforming takes place in the negative forming direction (towards the conical pressure chamber). The main aim of the negative preforming with the help of reverse drawing is to achieve a preform inline which permits the desired geometry to be obtained without thinning. This strategy permits the extension of the existing forming limits.

Other possible process strategies consist of a combination of the two variants described above. Here, the quasi-static or dynamic processes can be used either independently (3) or together on the same Hydropunch machine.

3 Numerical Model of Combined Working Media-based Forming

In order to determine the effect of the different quasi-static preforming operations on the course and result of pneumo-mechanical HSF, intensive experimental and theoretical research work was performed at the Chair of Forming and Machining Technology (LUF). One focus of this research work is achieving a reliable simulation of the process combination.

Furthermore, the forming of a workpiece with combined hydrostatic and hydrodynamic forming processes is influenced by a large number of parameters, including the locally acting pressure, the working media, the type of pressure chamber and the plunger geometry. In order to understand these process phenomena, to determine the interaction between key process parameters, and also to support/optimize the development of the new combined machine, use was made of FEA based on a coupled Euler Lagrange model (CEL). Here, both quasi-static and dynamic processes are represented in a single model. The modelling was carried out using the Finite Element Method and the explicit calculation type in Abaqus 6.14. The finite element mesh in the CEL model is represented by a stationary cube in which Euler and Lagrange elements move and interact with each other, see Figure 4. Here, the EC3D8R elements make it possible to model the Euler problems which are completely or partially filled with the working medium or material. The unfilled areas of the grids are automatically designated with the void material model. The volume fraction is recalculated in each iteration step and fed to the next calculation step, for more details see (Abaqus, 2014 and Smojver, 2010).

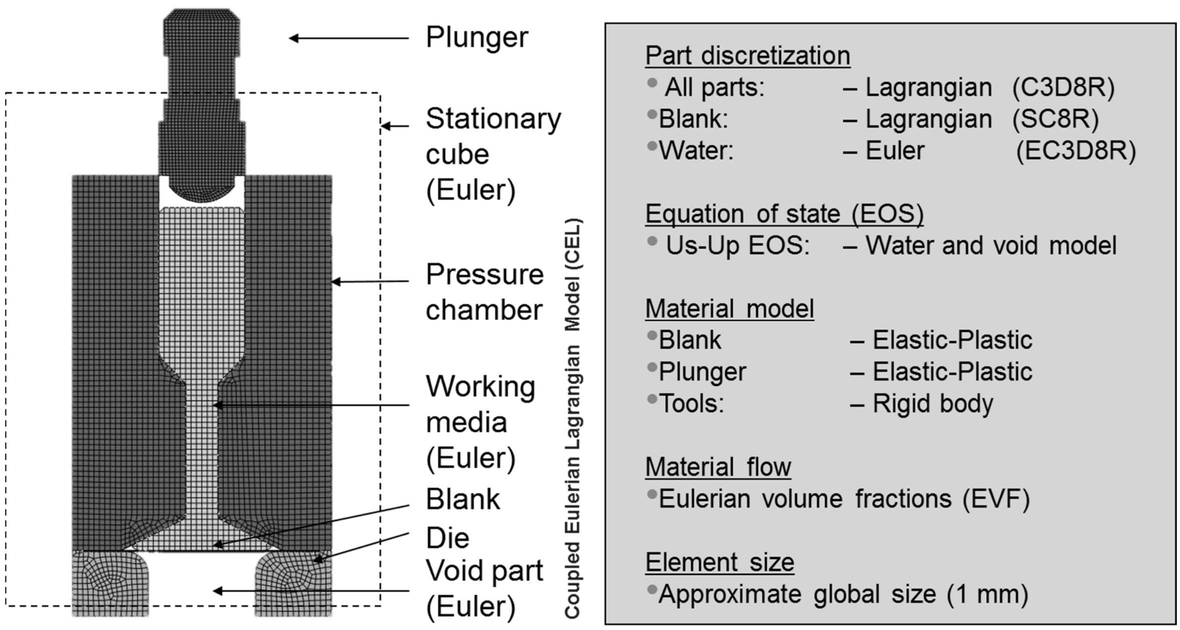

***Figure 4**: Numerical model of combined working media-based forming process*

In the first approach, the Us-Up equations of states were used to model the water movement, where the properties for the Us-Up EOS for water have been taken from (Vovk, 2008). These equations describe the working pressure states within a working medium as a function of the incompressibility, density and viscosity of the working medium. Furthermore, for modelling the preforming and forming operations of the semi-finished sheet metal parts, use was made of a simplified material model by Johnson Cook. The necessary Johnson Cook coefficients, the static and dynamic material density and also the Gruneisen coefficient were taken from (Vovk, 2007 and Zaizew, 2013). This material model makes it possible to determine material hardening during the quasi-static forming process as well as the plastic effects during dynamic forming. Due to the low forming speed during the quasi-static and pneumo-mechanical high speed forming processes, both the thermal effects in the material and the cavitation on the surface of the semi-finished part are neglected. These are also being examined in ongoing work at the LUF.

The CEL model that was developed was used for a detailed analysis of the influence and interaction of the process parameters with the pressure and distribution during pneumo-mechanical high speed forming or calibration processes and was conducted in addition to the experimental investigations into the influencing parameters and the work on drawing up the concept for the new machine and process design. Initially, the pneumo-mechanical forming process was examined numerically with regard to the influence of the plunger and pressure chamber geometry on the pressure effect and the pressure distribution. In order to validate and calibrate the simulation results and to determine the pressure distribution and effect, use was made of a phenomenological approach (Homberg, 2012). This approach is based on the determination of the resulting local spherical dent and radius R in a multiply-bulged sheet metal part. The radius height of the dent is a (local) indicator of the acting pressure. According to the Laplace formulation for spherical elements, the acting pressure can be calculated using the following equation:

$$P = \frac{2\,\sigma\,t}{R} \qquad (1)$$

With σ = tensile strength, t=thickness of the semi-finished part, R= radius of the spherical dent, see also Fig. 5.

4 Influence of Plunger Geometry Through Contact with Working Media

Due to the fact that the required pressure pulse with PMF is generated through the plunger dipping into the water-filled pressure chamber, it is obvious that the contact geometry of the plunger and the chamber geometry will influence the course and result of pneumo-mechanical forming processes. For this reason, dulled and staged plunger geometries were used during the investigation into the influence on the pressure effect and the pressure distribution. Analyzing the results of appropriate experimental and simulation-oriented research work, it can be seen that, while maintaining the same plunger impact velocity and process parameters, a dulled plunger geometry leads to a higher pressure and higher sheet deformation in the center of the blank than staged geometries, see Fig. 5. Analyzing the forming height distribution of the deformed parts during the experimental validation, it can be seen that the absolute and simulated pressure levels in the working area tally well in qualitative terms. Depending on the plunger geometry, the modeling process shows pressures approximately 12% to 18% higher in the center of the workpiece than the analytical pressure calculation in accordance with the Laplace formulation. Based on the present experimental and analytical results, it can be stated that the dulled plunger geometry leads to higher pressure effects under the same impact velocity. The staged and dulled geometries have no influence, or only a minor influence, on the pressure distribution and the impulse duration. The radial deviation of the forming height is thus less than 5 %.

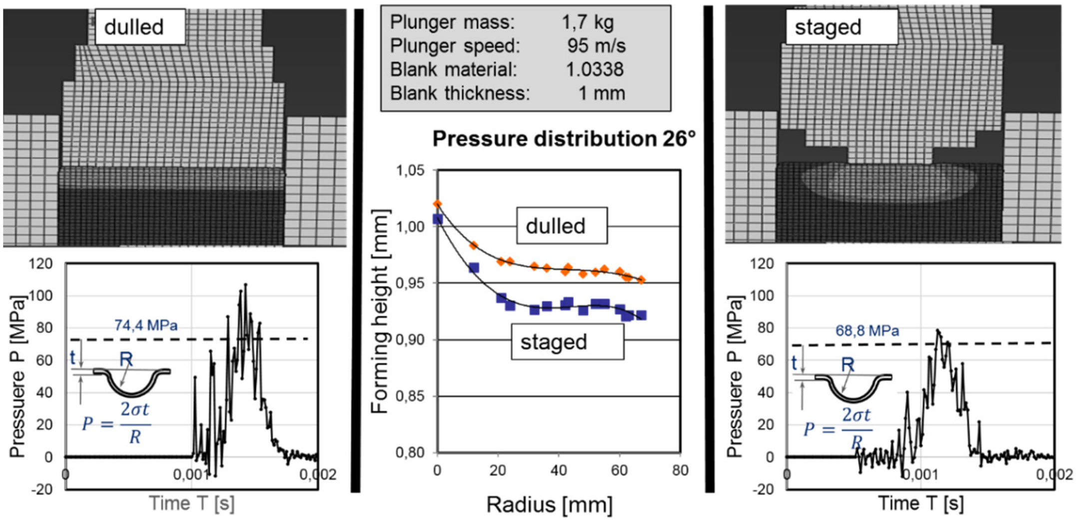

***Figure 5**: Influence of two different plunger top geometries of pressure pulse*

Taking into account the knowledge that shock waves are strongly influenced in their propagation behaviour by the surrounding compartment, it is necessary to examine this effect during PMF. Fig. 5 shows the result of a corresponding FEA investigation by way of an example. It can be seen that decreasing the pressure chamber angle leads to a decrease in the pressurized zone. Increasing the angle from 45° to 65° leads to a homogeneous pressure distribution in the radial direction on the part surface. But, increasing the angle to above 45 ° reduces the dent height or pressure by up to 20 %.

Furthermore, the experimental investigation of the forming height or the pressure distribution reveals the same trend as in the simulation. Here the results show that, with a pressure chamber angle of 26°, the highest pressures are clearly reached in the center of the workpiece up to a radius of 20 mm. Then, the forming height or pressure remains lower and constant with the result in a decreased forming height. The percentage deviation of the forming height between the inhomogeneous and homogeneous area is around 5%. A further increase in the impact velocity of the plunger up to 110m/s leads to a more inhomogeneous pressure distribution, which can be seen from the inhomogeneous sheet forming. Here, the highest pressures are also reached in the center and up to a radius of 20 mm. So it can be stated that, as a function of the pressure chamber angle, there is a definite limit at which the inhomogeneous pressure effect stagnates. The investigation of these limits and the optimization of significant process parameters is the subject of ongoing research work.

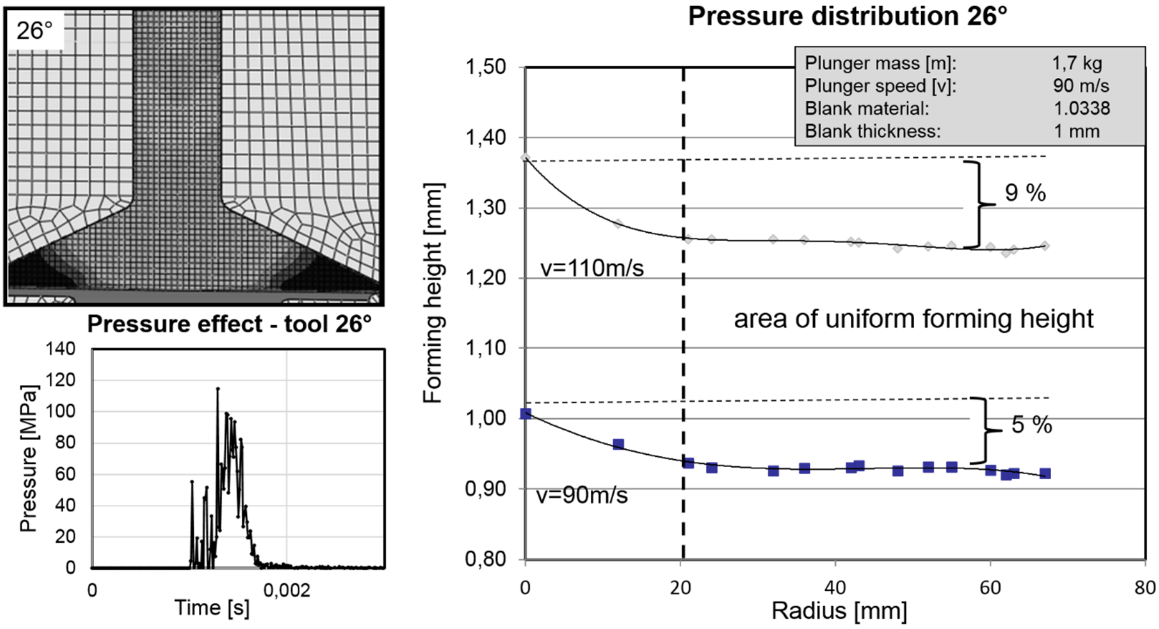

Figure 6*: Influence of the pressure chamber geometry pressure effect and distribution*

5 Setup of the new Combined Hydropunch Machine

To validate the theoretical results, and enable a detailed experimental investigation of the process combination, it is necessary to have a special experimental setup. For this reason, a new experimental machine was built, based on both the described results of the simulations performed and the experimental and theoretical research work carried out at the LUF. Here, high-pressure sheet metal forming and the pneumo-mechanical high speed forming process (Hydropunch) were selected as procedural representatives for the combined forming process. The following requirements have to be taken into account on the new machine:

- the combined machine has to allow different process sequences of positive preforming (form fill) and negative preforming operations (reverse drawing) as well as dynamic calibration;
- the sequential forming has to take place in the same tool, with the same clamping device
- the new pneumo-mechanical machine has to permit sequential and separate application of the quasi-static and dynamic sheet metal forming processes; and
- the same sealing principle for the pressure chamber has to be used for quasi-static and dynamic processes;

Figure 7 shows the setup of the combined pneumo-mechanical high speed forming machine (CPMF) with a tool unit for symmetrical and non-symmetrical sheet metal forming. Based on the fundamental principles of pneumo-mechanical high speed forming machines from Mazukin J.G. (1961), Tominaga H. (1967), Chachin B. A. (1972), Zuravskij J.A. (1994), Bragin A.P. (1995), and Kosing OE (1997), Frolov E. A (2008), Vovk A. (2004), the new CPMF machine consists of two pressure generation units (hydraulic and pneumatic), a vertically arranged acceleration tube and a two-part forming tool. The forming tool consists of a conical pressure chamber and a die with the base plates. By comparison to spherical or rectangular pressure chamber shapes, the conical chamber shape makes for a more homogeneous pressure distribution on the part surface during the forming processes (Vovk 2008). In contrast to other hydroforming and PMF machines, no expensive presses are used for locking the tool. Here, the two halves of the forming tool are clamped during the preforming and forming process with the help of two locking rings. This type of mechanical locking makes it possible to attain the forces from quasi-static forming pressure process up to 10 MPa as well as dynamic pressures of up to 175 MPa locally. Furthermore, by contrast to all other systems, the new machine with its newly developed hydraulic and venting system in the lower and upper forming tool permits bidirectional preforming as well as the required venting of the tool cavity for PMF. This means that the combined machine, which was developed at LUF, permits a combination of the advantages of quasi-static high pressure sheet metal forming and pneumo-mechanical high speed forming on one and the same forming machine.

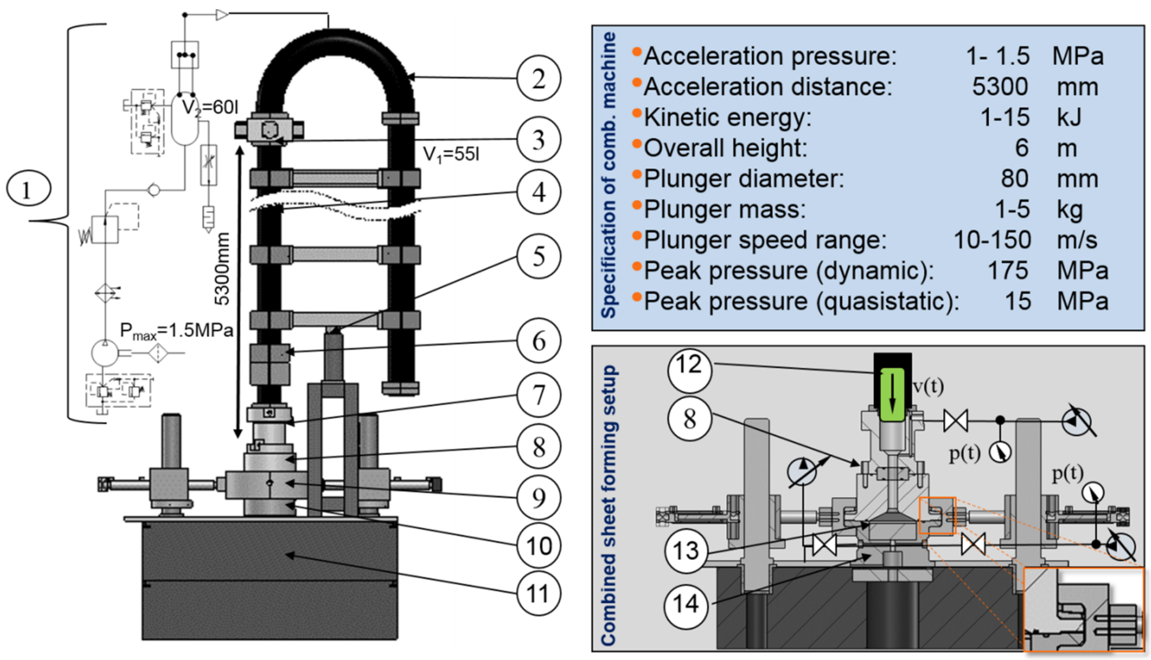

***Figure** 7: Pneumo-mechanical setup: 1 – pressure generation unit with secondary pressure tank; 2 – primary pressure tank; 3 - release mechanism; 4 – acceleration tube; 5 – lifting device; 6 – light barrier; 7 – tube adapter: 8 pressure chamber; 9 – locking ring; 10 – lower tooling adaptor (die); 11 machine bed; 12 – plunger; 13 – base plates; 14 – vent port.*

The principle of the so-called Hydropunch machine or the alternative method for the pressure wave generated in a working medium by means of an accelerated plunger was developed by Mazukin J.G. in 1961(Bragin, 2007). The principle is that, for the generation of pressure waves in the working medium which is enclosed in a pressure chamber, the working medium is loaded through impulse generation by a fast-flying plunger. The plunger dips into the working medium, reaching the desired speed at the end of the accelerating tube, and thus generates very short and high pressure pulses up to several dozen MPa due to the kinetic movement of the plunger and the incompressible properties of the working medium. In order to accelerate the plunger in the new machine, use is made of compressed air pressure. The maximum acceleration pressure is 1.5 MPa, the length of the acceleration tube is 5.3 m and the diameter used is 80 mm. At the lower end of the tube there is a device for measuring the plunger speed in order to determine the plunger energy. Below the measuring device a ventilation system is located, in order to limit the proportion of compressed air in front of the plunger during the downward movement. The measurement of the pressure distribution and the pressure effect is performed using a phenomenological approach, more details of which are given in (Homberg, 2012). The quasi-static working media pressures are generated by means of a pneumatically driven high-pressure pump from the Maximator company. The transmission ratio amounts to 1:44 MPa. During the dynamic processes, a technical vacuum is created in the cavity of the lower die which amounts to 0.005MPa.

6 Technologically-oriented Research Work

Besides the support for machine design, basic research regarding the effect and interaction of parameters on the course and result of the PMF process was carried out at LUF. By way of example, one result shows that the thickness distribution of an equally formed conical part can be strongly influenced by the selected preforming strategy, see Fig. 8. Here, the investigation into the thickness distribution showed that, due to higher stretch forming, the classical PMF process leads to a 25 % thinning of the base material. In this case of classical PMF, the highest thickness variations obviously occur directly on the drawing radius. Then, the thinning level remains homogeneous in the radial direction on the blank, at 21%. The same thickness profile is also attainable with the negative preforming (RD) strategy, but with a lesser thinning of the base material. In contrast to a single PMF forming operation, negative preforming leads to a wall thickness reduction of only 8% or so. Furthermore, the positive preforming strategy shows that both the thickness profile and the thinning can be optimized. The positive preforming permits a uniform thickness reduction profile extending from the drawing radius to the center of the workpiece. However, the positive preforming strategy compensates the thinning for the same degree of forming by up to 5%. Moreover, analyzing the forming height distribution of the deformed parts, it can be seen that the resulting forming, as well as the sheet thickness distribution can be readily approximated by the CEL-Model developed, see Fig. 8. The resulting deviation between the experimental investigation and the simulation results is lower than 12%.

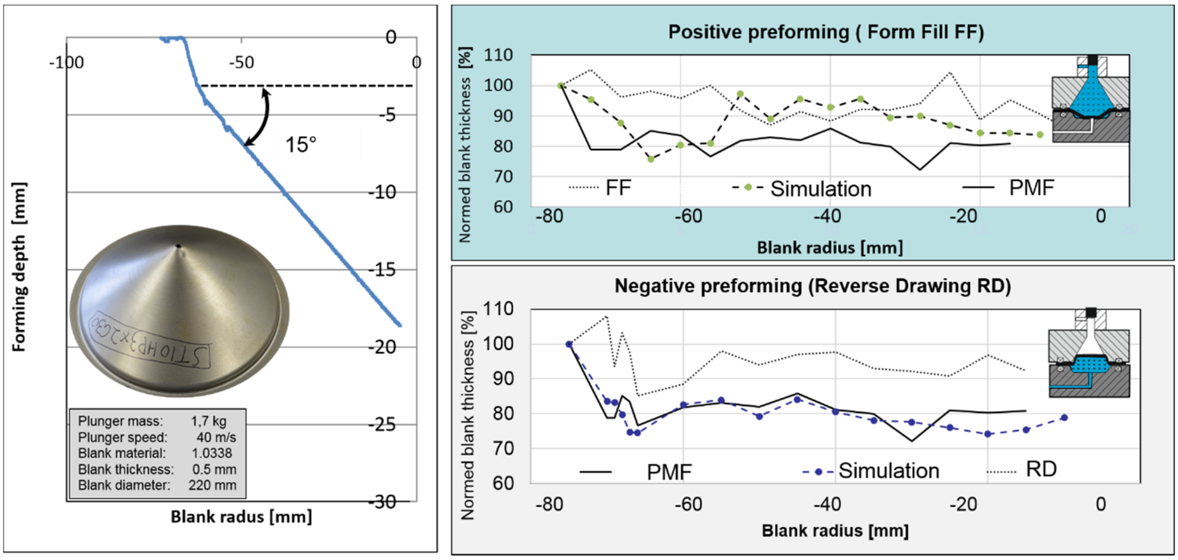

***Figure 8**: Influence of the preform strategies onto thickness distribution and profile*

7 Conclusion

This paper presents a possible process combination of quasi-static and high-speed-working media-based forming processes, where the advantages of quasi-static high pressure sheet metal forming and pneumo-mechanical high speed forming are combined using a special high speed forming machine. It presents new forming strategies for the preforming, forming and calibration of the sheet metal parts by means of the working media. Moreover, the paper shows validated numerical results for the influence of significant process parameters, such as the pressure chamber angle and plunger geometry, on the pressure distribution when using the pneumo-mechanical forming high speed processes. So the variation of the chamber angle showed that the chamber angle, for example, can effectively increase the homogeneity of the pressure distribution during the forming. A comparison of positive and negative preforming strategies, showed that it is possible to achieve lower and uniform thickness reduction with the aid of the two above-mentioned strategies compared to the conventional quasi-static or dynamic processes. To conclude, the combined forming processes have a high potential for producing complex geometries through the optimal use of the formability of the material employed.

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