Process reliability and reproducibility of pneumo-mechanical and electrohydraulic forming processes

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Abstract

A sufficiently high process reliability and reproducibility is mandatory if a high-speed forming process is to be used in industrial production. A great deal of basic research work into pneumo-mechanical and electrohydraulic forming has been successfully performed in different institutions in the past. There, the focus has been more on process related correlations, such as the influence and interaction of different parameters on the course and result of those processes. The aspects of reliability and reproducibility have not been examined to a sufficient extent. Hence, in the case of pneumo-mechanical forming, insufficient investigations have been conducted into the effect that key parameters like the kinetic energy level, the filling height of the working media or the conditions inside the acceleration tube have on the reproducibility and course of the process. For electrohydraulic forming, the repeatability has worsened on occasions up to now. To improve the forming results and, in particular, the reputability of the process, it is necessary to examine the tool parameters associated with the electrodes and the working media. That is why research of this type is currently ongoing at the LUF. One important issue here is examining the options that exist for visualising the way the spark takes hold in the discharge chamber.

Keywords

High Speed Forming, Pneumo-mechanical Forming, Electrohydraulic Forming

1 Introduction

The global trend towards the sustainable use of rare resources and the increasing demands of consumers for security items for products, for example, are leading to more complex components that are subject to high quality requirements. Due to the current processing limits, classical stamping processes like deep drawing or conventional hydroforming frequently fail to provide usable production results. Hence, there is a need to develop innovative production processes for industrial use which can meet up to these requirements. In this context, pneumo-mechanical (PMF) and electrohydraulic (EHF) high speed forming processes have a high potential [2][5][6], since they can increase the formability of large numbers of materials and, through that, produce more complex geometrical shapes. At the same time, high-speed forming (HSF) processes are particularly energy efficient compared to conventional forming processes. The technology of high-speed forming processes has been known since the 20th century already, when intensive research work was performed in the United States, Germany and the Soviet Union in particular [1], focusing on the correlation between the different process parameters and their influence on the forming result. Several working principles, including the use of explosives and electrohydraulic or pneumo-mechanical pressurization, are used in both research work and industrial practice.

MAZUKIN J.G. first introduced the principal of pneumo-mechanical high speed forming in 1961, using compressed air inside a pipe to accelerate a plunger diving into the working media filled pressure chamber. An initial investigation showed that pressures up to 1200 MPa and energies of 60 kJ in the working media were possible [2][3]. Typical process times were only a few milliseconds. The first known prototype machine based on the pneumo-mechanical principle was developed by TOMIGANA and TAKAMATSU and was presented in 1964 [3]. KOSING and SKEWS presented a further development of this principle by dividing the tube into different sections using membranes to transfer the energy from one section to the next [4]. FROLOV used this method not only for forming operations like stretch drawing but also for cutting operations, where the plunger was used as a stamp, with no working media in the chamber. The cutting result depends on the attainable energies as well as on the properties of the blank, including the blank thickness [5]. So far, the pneumo-mechanical method has only been used for the production of small tube and sheet metal parts. In the Soviet Union and the United States, more than 35 machines for stamping, cutting and metal forming were developed up until the 1990s. At present, a number of research projects using similar pneumo-mechanical high speed forming setups are focused on the further investigation of the process and material parameters in order to achieve an in-depth understanding of process phenomena and improve on the simulation models for high speed forming processes [2][6]. Furthermore, certain research institutes in the Ukraine and Russia are attempting to create new and more efficient tool systems and develop new pneumo-mechanical forming machines with innovative, efficient energy sources, such as the use of environmental fuels, electricity or explosives for the acceleration of the plunger and its impact on the forming result [7].

The electrohydraulic effect was first introduced by SVEDBERG in 1905, who used it for rock fragmentation [9]. The further development of this effect in the 1960s led to its implementation in different industrial sectors like the forming (EHF) of tubes and blanks, rock fragmentation and medical applications such as lithotripsy [8]. In the 1960s, in particular, a large number of scientists from many different countries attempted to understand the processes phenomena and developed working tools for forming tubes and blanks [11], but only a minority of them tried to set different process parameters to achieve specific forming results, such as HAMMANN et al. [9] and HÄUSLER et al. [10]. Both investigated the effect of different process parameters, such as the wire diameter and material and the conductivity of the working medium on the forming result with tubes. KNYAZYEV was the first to investigate the pressure distribution on the blank in conjunction with different numbers of electrodes, employing a phenomenological approach for calculating the pressure level [12][18]. So far, the EHF technology has been successfully used for deep drawing, calibration, expansion and joining processes, for example [1][13].

Current research work in the above-mentioned countries and also at the LUF is focused on the development of pneumo-mechanical and electrohydraulic processes for industrial use.[13][14][17][18] It is thus essential to investigate the reproducibility and reliability of these processes and the influence of different process parameters.

This paper presents recent research results for PMF and EHF with regard to the influence of different process parameters on the forming result, and especially on the reliability and reproducibility of each of the processes. Using these results, it will be possible to boost the reputation of these high speed forming processes and put them to industrial use in future.

2 Experimental setups and measurement techniques

To investigate the reproducibility and reliability of PMF and EHF, different tests were performed with the aim of analysing the influence of different process parameters such as the venting level of the acceleration tube and the working media on the course and result of these processes. Important information about the reproducibility and the reliability of these processes is provided by an analysis of the formed parts on a coordinate measuring machine (CMM). Here, a phenomenological approach [5,6] was adopted, where sheet metal blanks were formed into a die with multiple cylindrical recesses, producing dents in the blank, which are located on specified radii on the blank. This method is also known as the multi-point-membrane method and is successfully used in other research institutions for determining the cavity pressure and pressure distribution during HSF [9][18]. The CMM is able to measure the overall geometry of the formed blank, recording the highest point of each dent for further analysis (Figure 1). This analysis shows the forming height as a function of these radii. With this information, it is possible to draw conclusions on the reproducibility and the pressure distribution acting on the blank [4].

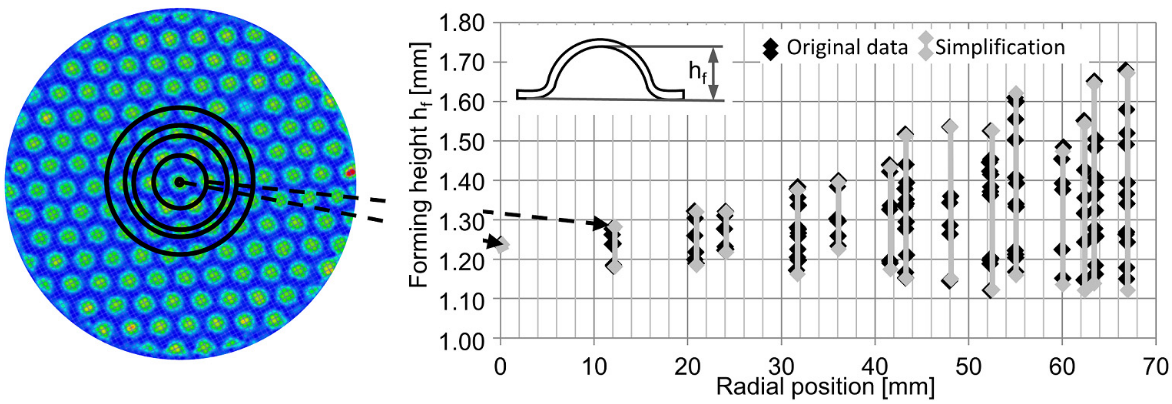

Figure 1: *Measurement and illustration of the results using the CMM*

An optical 3D forming (GOM, Argus) analysis system was used to investigate the forming limits attained and to visualize these.

2.1 Setup for pneumo-mechanical forming (PMF)

The pneumo-mechanical setup consists of a pressure generation unit, a vertically arranged acceleration tube and a working tool used to form sheet metal blanks into a die (Figure 2). Inside the tube, a plunger is accelerated by stored, compressed air and dives into the water-filled chamber, thereby generating very short pressure pulses of up to 100 MPa for forming sheet metal blanks in a die. The maximum acceleration pressure p_a is 1.5 MPa, the length of the acceleration tube is 5.1 m, and the tube diameter employed is 38 mm. At the lower end of the acceleration tube, there are several vent holes for releasing the air in front of the plunger. Depending on the size, number and position of the venting holes, the set acceleration pressure and the filling level in the pressure chamber, it is possible to vary the number of plunger impacts and hence the number of pressure pulses during a forming process. Above the vent holes, at a distance of 300 mm from the forming tool, there is a device for measuring the plunger speed (two light barriers) in order to determine the plunger energy. A high-frequency ICP pressure sensor (109C11) from PCB performs pressure measurements inside the chamber.

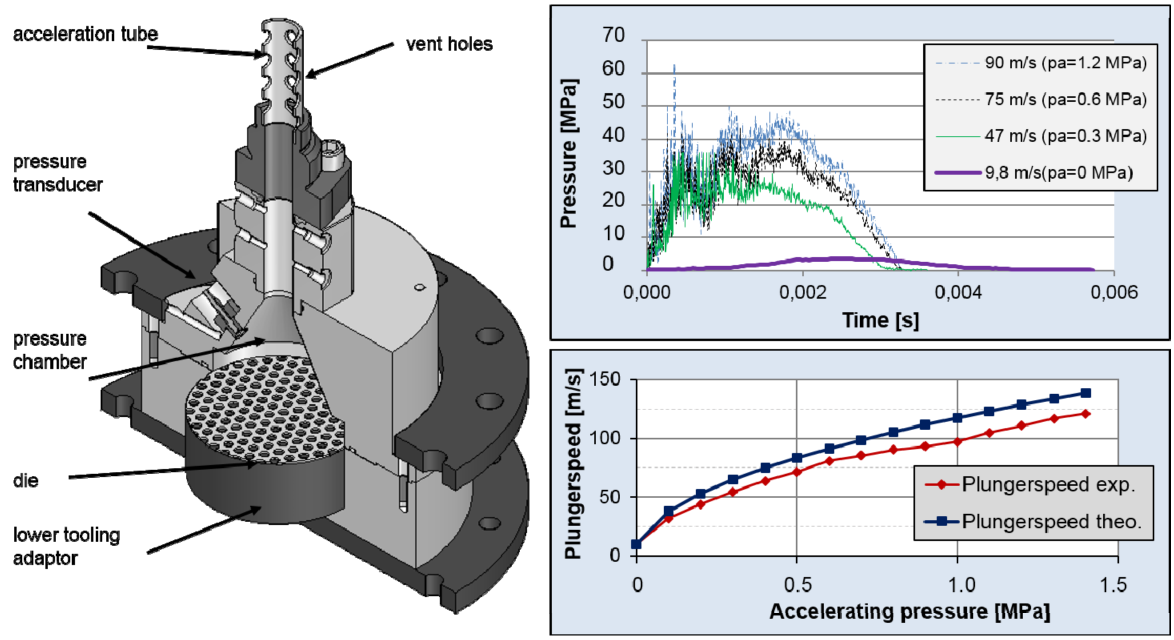

Figure 2: *Cut-away of the current PMF-tool for forming sheet metal blanks and process characteristic of PMF (dynamics of wave pressure at the top of the workpiece and impact velocity of the plunger in correlation to the accelerating pressure)*

2.2 Electrohydraulic setup

The electrohydraulic setup consists of a pulse power generator containing two capacitors from Poynting GmbH, Germany, which is connected via a coax-cable to the EHF-tool used for sheet metal forming (Figure 3). With a capacity of 15 µF (per capacitor) and a maximum charging voltage of 20 kV it is possible to obtain a maximum charging energy of 6 kJ. When using two capacitors a maximum current of 160 kA can be achieved. Overload tests with 9 kJ and 25 kV are also possible. The present working tool contains two electrodes, which are installed opposite each other and connected by a constantan wire (CuNi44). The blank to be formed is located on a perforated blank as the die, which provides the desired geometry. The discharge chamber has to be filled with a working medium, which is often water. When running the process, a Rogowski-coil measures the discharge current and an oscilloscope records it.

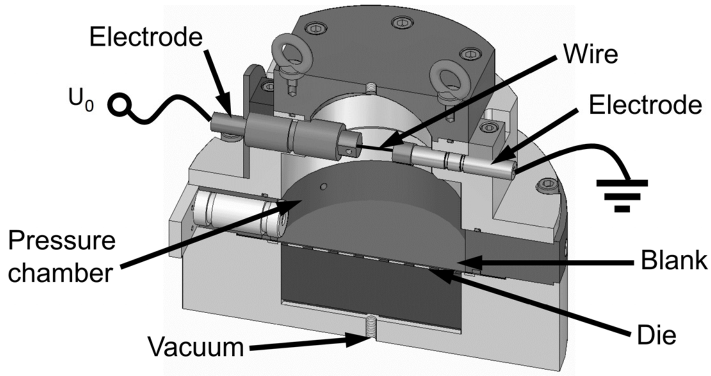

Figure 3: *Cut-away of the current EHF-tool for forming blank materials*

3 Results and Discussion

The focus of this work is on analysing the influence of different process parameters on the forming result, and especially on the reproducibility and reliability of each process, with the aim of making pneumo-mechanical and electrohydraulic forming suitable for industrial use.

3.1 Influence of the venting level on the forming result using pneumo-mechanical forming (PMF)

Previous work on pneumo-mechanical forming has shown that the resulting pressure pulse has a major influence on the reliability and reproducibility of the forming result, which is determined primarily by the working media and the kinetic energy, see [5-9] for detailed information. The kinetic energy depends on the acceleration distance, the mass of the plunger, the level of the acceleration pressure and the venting of the acceleration tube. One important aim of the current research work is to analyse the influence and interactions of the kinetic energy and the venting of the acceleration tube on the forming result with PMF. These results will make it possible to draw conclusions regarding the reproducibility and reliability of the process.
Due to the fact that the plunger displaces the air in front of it inside the tube as it moves, it is obvious that this resistance has a major influence on the attainable kinetic energy of the plunger and hence on the course and result of PMF. Previous work has shown that, at high acceleration pressures in particular, a lot of the kinetic energy is wasted due to the air resistance by comparison to simple theoretical calculations. Hence, a higher energy is necessary to achieve the same forming levels as those worked out theoretically.
To analyse how the venting of the tube influences the forming result as a function of different pressure conditions, several tests were performed varying the size of the venting holes from 0 mm² to 2,500 mm² (Figure 4).
Experiments without venting holes showed hardly any forming of the blank, due to the above-mentioned air resistance in the tube at all acceleration pressures. An increase in the venting area normally leads to more pronounced forming of the blank, attaining a maximum at 1,300 mm² when applying a 3-bar acceleration pressure. A further increase in the size of the venting area reveals a reduction in the forming level for the blank plus an increase in the deviation of the measured forming heights of up to 0.4 mm, thus leading to poorer reproducibility and reliability of the process. If the venting area is increased still further, the plunger speed or kinetic energy is so high that the plunger collides with the

blank, leaving dents or holes in the blank (Figure 4). These phenomena occurred with all the other accelerating pressures tested too, but at a much earlier point in time depending on the level of the accelerating pressure selected (see the collision line of the plunger in Figure 4), which meant that the maximum forming height, as shown at 3 bar, could not be attained. It can be assumed that, in this case, a lot of working media splashes through the venting holes during the plunger's first diving phase, so that the filling level is not sufficient to prevent the plunger from colliding with the blank during the first or subsequent immersion phases.

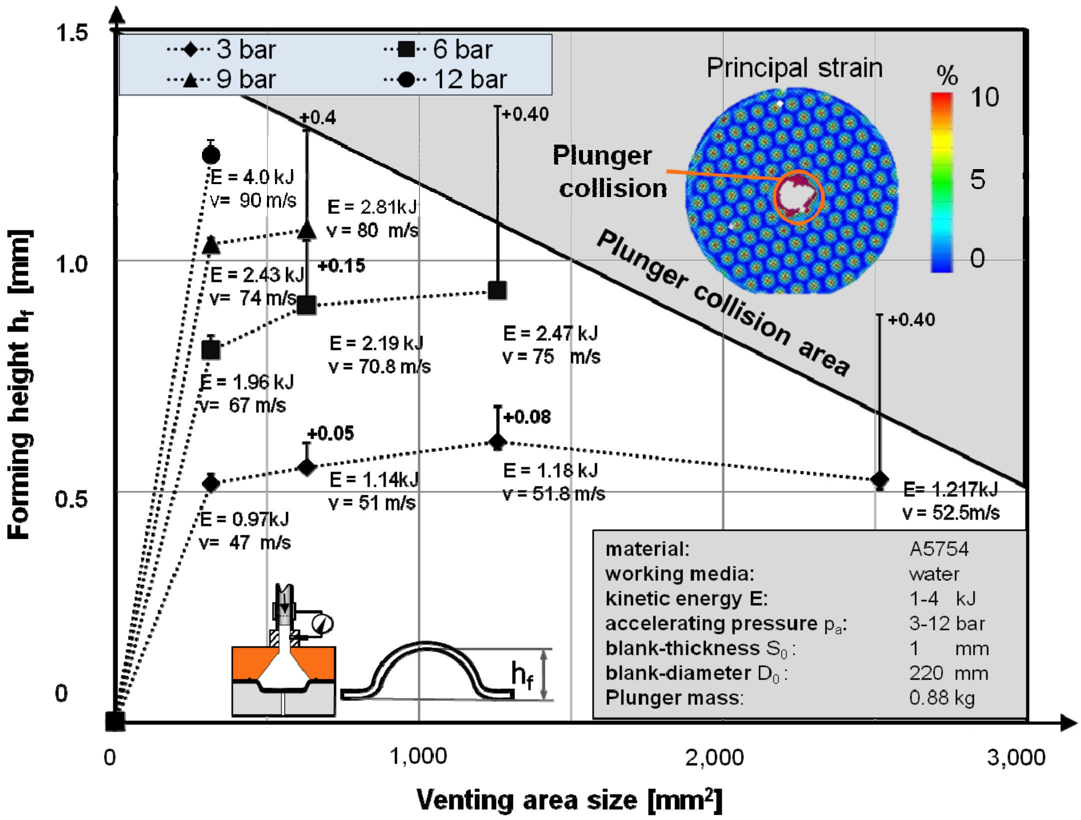

Figure 4: *Reproducibility of the forming results with different venting area sizes*

These findings led on to the question as to how the number of plunger impacts in the working media is influenced by the size of the venting area. Corresponding tests were performed with an accelerating pressure of 3 bar using an audio measurement system to record the punches of the plunger in the water. Figure *5* shows that without venting holes in the acceleration tube almost no forming of the blank occurs, with only one impact of the plunger on the water. The resulting pressures were identical to the pressure at acceleration pressure of 0 MPa, see Fig 2. By increasing the size of the venting area, the number of impacts increases to as many as 10. Here, a maximum number of impacts as well as the maximum forming height can be observed at approximately 800 mm². In the same way as for the curves in Figure 4, the forming height curves, the number of impacts decrease with higher venting areas but the scatter of the forming heights and also the plunger speed/ impact velocity(v) increases again, resulting in a worse reproducibility of the forming results.

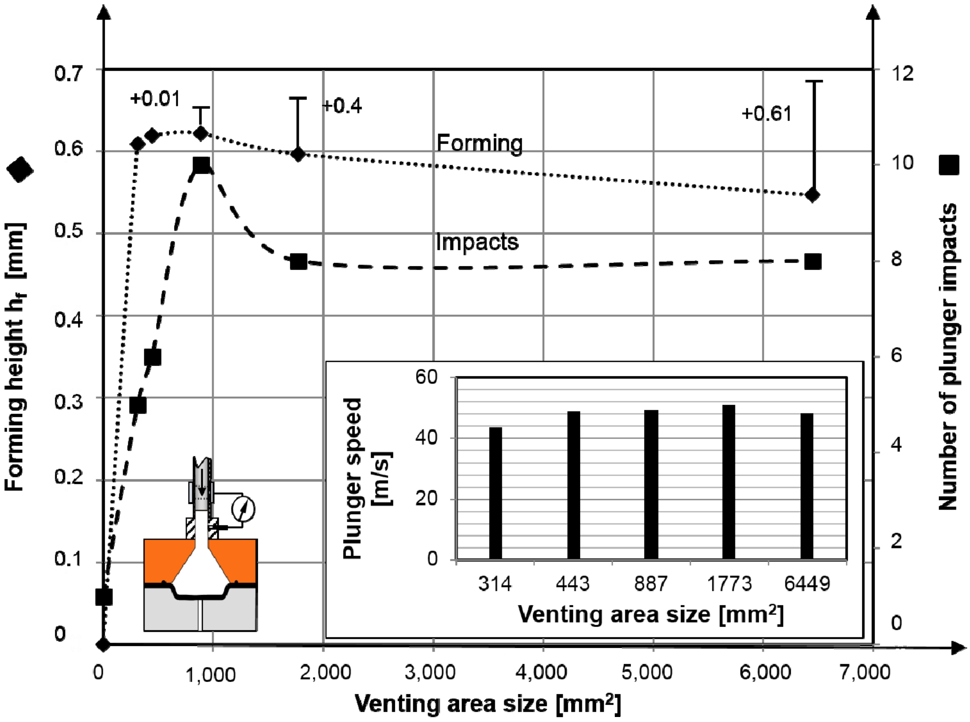

Figure 5: *Influence of venting level on sheet forming, plunger impacts and plunger speed*

Optical 3D forming analyses showed non-uniform forming heights of the dents in both tests, leading to the assumption that the pressure distribution that acted was not uniform either. This occurred especially with venting area sizes which exceeded the optimal area size, leading to reduced forming heights and plunger speeds. Here, the deviations of the forming heights were up to 0.61 mm in the radial direction of the part, leading to poorer reproducibility of the forming results. The maximum forming heights or pressures were obviously achieved in the center and also in the outer region of the workpiece.

Summarizing, it can be said that an increase in the size of the venting area leads to greater forming of the part and to a higher plunger speed, as well as to an increase in the number of plunger impacts with the water. Once these parameters have attained a given maximum, a reduction occurs in all of them in conjunction with an increase in the deviation of the forming heights. Increasing the size of the venting area further leads to the plunger colliding with the blanks. A boundary line was identified showing which parameter results in a plunger collision with the blank for the conditions examined.

The phases of the process during which the plunger collides with the blank, configuring the filling level of the working media to prevent a collision and establishing a means of influencing this finding in a positive way are all tasks to be solved in the future, aiming for better reproducibility and reliability of PMF.

3.2 Results of electrohydraulic forming (EHF)

To study the reproducibility of the forming height and the pressure distribution on the blank use was made of a die with a large number of recesses. By varying parameters like the load energy, the working medium and also the electrode material, it proved possible to analyse the influence of these parameters on the reproducibility of the process as well as to draw conclusions on the pressure distribution acting on the blank.

3.2.1 Influence of the working media type

Using water as a working medium is not always convenient due to handling difficulties and the corrosion problems with some blanks, such as the mild steel 1.0338 that was used. It is thus very interesting to try out different working media and see their influence on the results of the electrohydraulic forming process. By changing the working medium, it is possible to vary different parameters of the working medium employed, with the aim of achieving better forming results, i.e. pressure distribution and reproducibility. The first tests were carried out using the three different working media of borax slime[1], starch-water[2] and ethylene glycol. These media differ in their density, viscosity and conductivity as well as in their fluid-mechanical behaviour, since slime and starch-water are non-Newtonian and ethylene glycol is a Newtonian fluid. Slime and starch-water were chosen because of the good results achieved by HOMBERG for pneumo-mechanical forming [15] and ethylene glycol was chosen because of the good results obtained by HARTMANN, but using a different setup [19]. Representative results of each working medium for a load energy of 2 kJ by comparison to results using water at 1.75 kJ are shown in Figure 6.

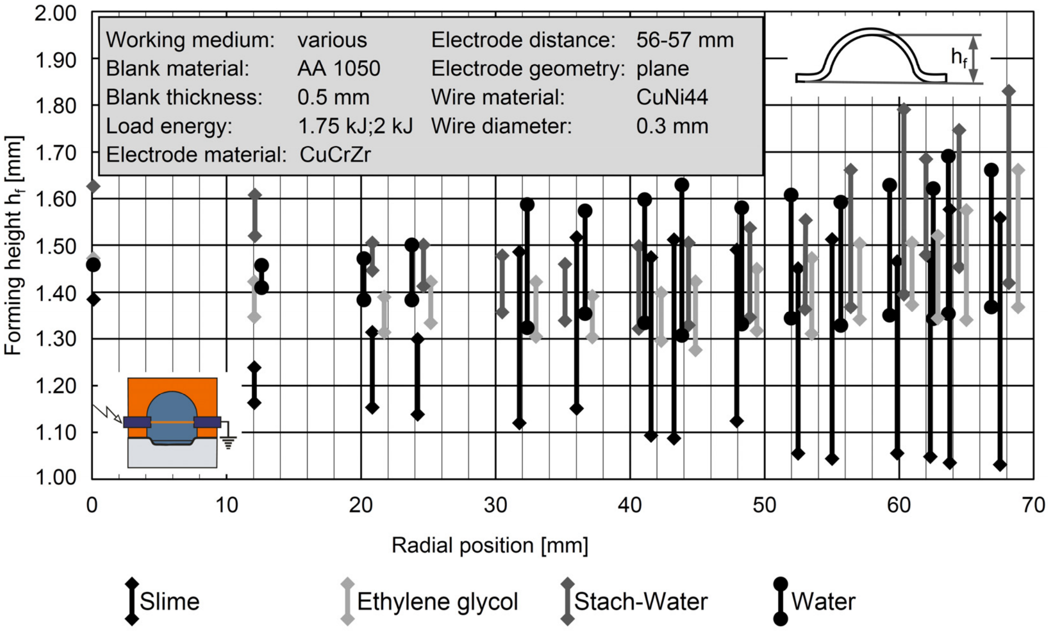

Figure 6: *Representative forming results with different working media using EHF*

With the exception of ethylene glycol, all the other working media generated a non-uniform pressure distribution on the blank. The forming height range extends up to 0.43 mm when using starch-water, for example, which is very high by comparison to ethylene glycol. Here, the forming height range is much lower in the middle of the part, but quite high in the outer radii. This is due to the reflections of the working media waves on the tool surface. While the forming heights of the dents with ethylene glycol, starch-water and water are comparable to each other, slime shows a much lower forming height level in some cases.

[1] Slime: mixture of borax ($Na_2B_4O_7$) with polyvinyl alcohol ($(-C_2H_4O)_n$) and distilled water
[2] Starch-water: mixing ratio of 1.5 starch/1 water

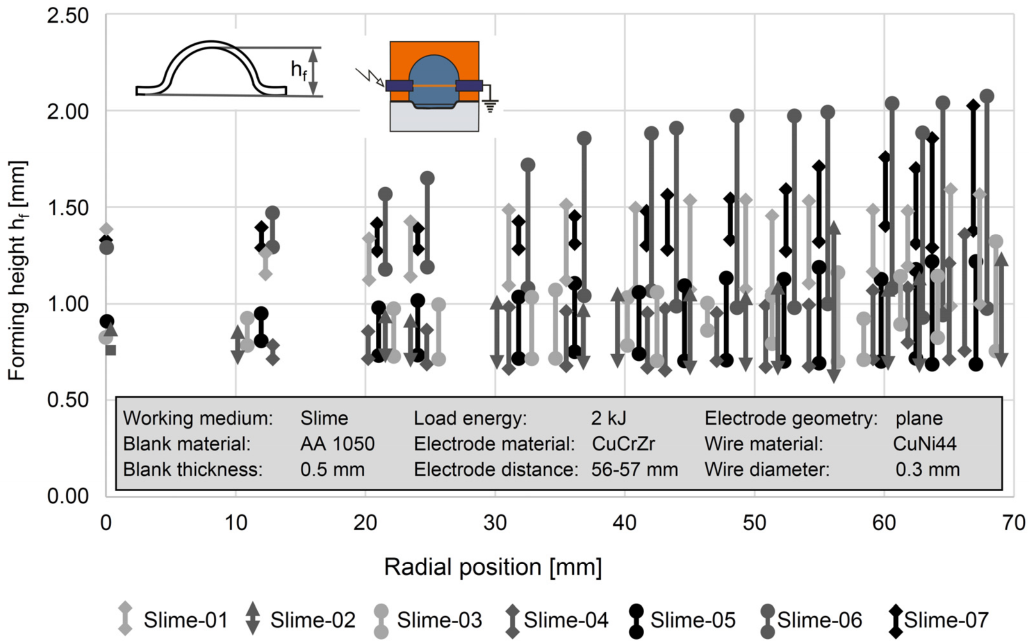

Figure 7: *Reproducibility of the forming results and discharge process of slime at 2 kJ*

While all the other working media showed quite good reproducibility of the forming results, of about Δ < 0.1 mm in most cases when keeping all the process parameters constant, slime had the worst reproducibility and displayed different discharge currents and forming heights (Figure 7). Very different forming heights and a very high scatter of the forming heights is evident on each radius. This high scatter in the forming height, and especially in the outer radii, results in the assumption that the spark did not follow the path to the mass-electrode but took a shorter and more convenient route to discharge on the inside of the working tool. Hence the pressure wave was not formed in parallel to the blank, but at an angle to it, and proceeded up to the corner of the discharge chamber. This can constitute an explanation for the one-sided pressure distribution, which is confirmed by the pictures taken by an optical measuring system (Figure 8).

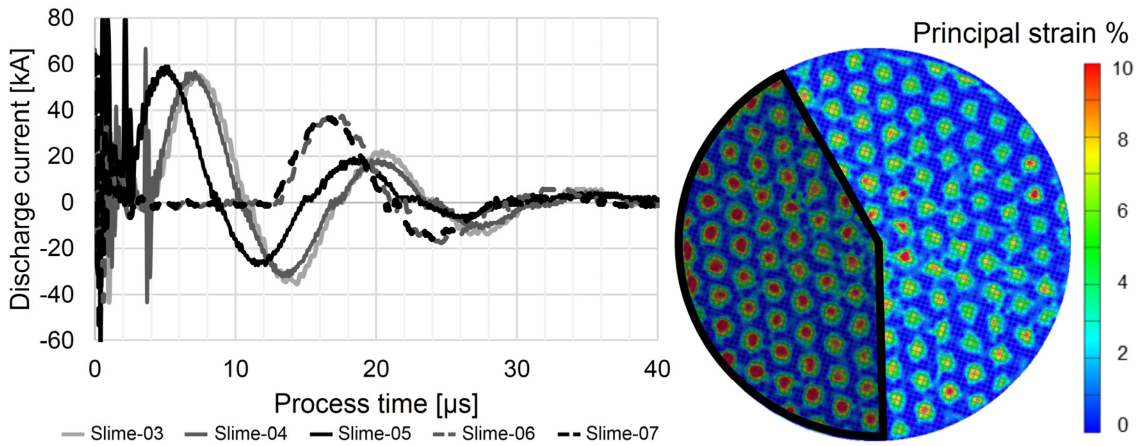

Figure 8: *Discharge current and optical measurements of the forming load*

The discharge-current measurements reveal two different types of curve. The first is the expected discharge current (Figure 8) showing a so-called dark phase and, after that, an oscillated discharge of the capacitor bank. On the other curve, the dark phase is missing completely, which confirms the assumption of a different discharge route being taken.

These results show that the working medium has a major impact on the reproducibility of the forming results. Using different working media has the advantage of making it possible to visualize the way the discharge took place in the working media by removing it in layers. Hence, the factors that influence the discharge route can be analyzed and, with this information, it will be possible to stabilize the discharge process, which will lead to better reproducibility of the forming results and to more uniform pressure distribution. Figure 3-5 shows examples of burning marks in slime and starch-water.

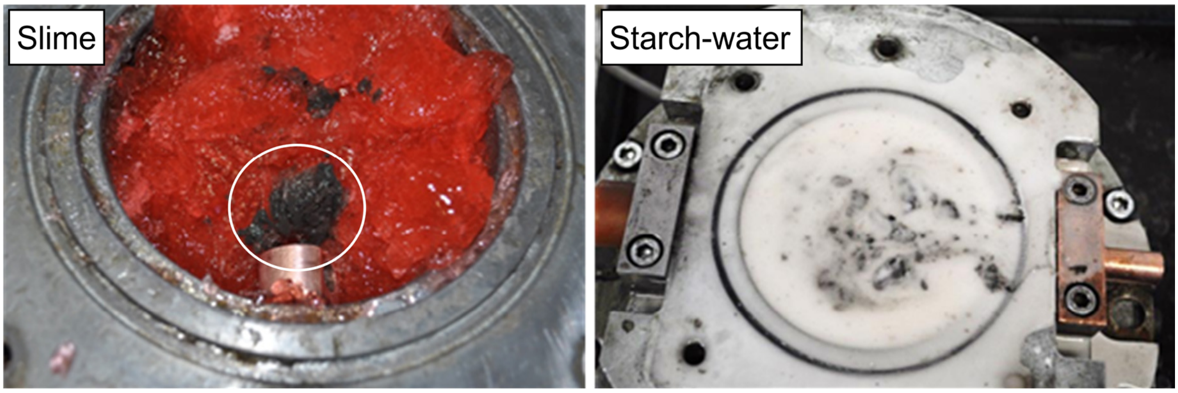

Figure 9: *Burning marks in slime and starch-water produced after one discharge*

3.2.2 Influence of the electrode material

Further experiments were conducted using different electrode materials with the aim of analyzing the influence of the electrode material on the reproducibility of the forming results (Figure 10).

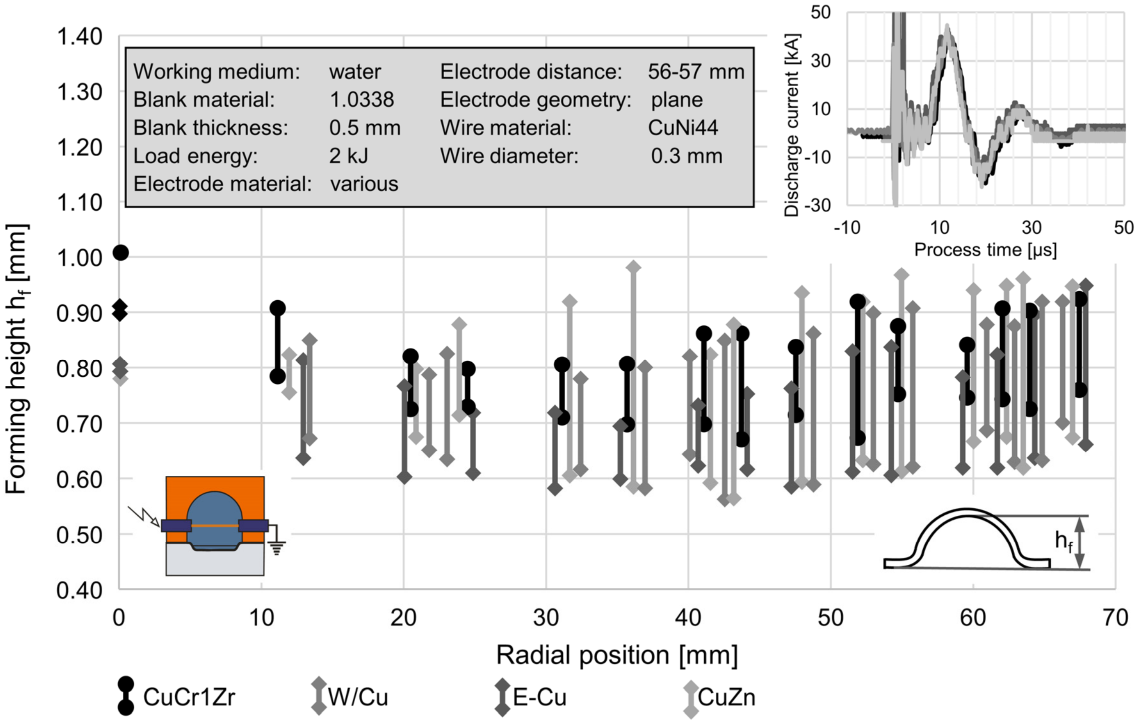

Figure 10: *Forming results using different electrode materials*

These results show that reproducibility of the forming results is achieved when the same parameters are used. If different electrode materials are compared, however, it can be seen that the range of forming heights within a single radius extends from Δ=0.22 mm with CuCr1Zr-electrodes to 0.43 mm with E-Cu (Figure 9). It also can be seen that, when using CuCr1Zr-electrodes, the pressure distribution is more uniform than for all the other materials tested. The comparison of the discharge currents shows mostly the same behaviour of all materials. Here, E-Cu and CuZn show a rise in the current of 5 kA compared to the other materials. Hence, it is obvious that the choice of electrode material can influence both the reproducibility and the pressure distribution on the blank but doesn't influence the discharge current significantly. In our tests, CuCr1Zr-electrodes showed both the best reproducibility and pressure distributions.

4 Conclusion

The subject of this paper was to identify the influence of significant process parameters on the reliability and reproducibility of the pneumo-mechanical and electrohydraulic forming processes. In the case of pneumo-mechanical forming, it was shown that a minimum venting level is absolutely essential for the homogeneous and efficient forming of sheet metal parts. A certain increase in the optimal venting level leads to a reduction in the forming heights and yet also to an increase in the geometrical deviation within an individual blank. The reproducibility and reliability are thus given within a particular frame but ought to be improved by analysing the effects leading to the results presented.
In the case of electrohydraulic forming it was shown that process parameters like the working media type and the electrode material can influence the forming result and the course of the process. For future work, it will be essential to better visualize the way the discharge takes place in the discharge chamber so as to be able to stabilize the discharge process. This will result in better reproducibility and reliability of electrohydraulic forming.

References

[1] *Wilson, F.*: High Velocity Forming of Metals. Prentice-Hall International, London, 1964

[2] *Bragin A.P.*: Hydrodynamical forming on pneomomechanical high speed forming machines. Journal of aerospace technique and technology, 2007, P. 296, Ukraine

[3] *Tominga*, *H.*; *Takamatsu*, *M.*: Hydropunch, a pneumatic-hydraulic-forming machine.2. International Conference of the Center for High Energy Forming, Estes Park, USA,1969

[4] *Kosing, O.E.*, *Skews*, *B. W.*: The use of liquid shock waves for metal forming; 21st International Symposium on Shock Waves, Great Keppel Island, Australia, 1997

[5] *Frolov, E-A*: Technologiceskie vozmoznosti processa impulsnoj stampovki elasticnoj sredoi. Kuznecno-stampovocnoe proizvodstvo, obrabotka materialov davleniem. Band 36, Heft 9, Moskau 1994

[6] *Vovk, A.:* Verfahrensentwicklung zur Fertigung qualitätsgerechter Bauteile mit dem Hydro-Impuls-Umformen von Blechen, Dissertation, Magdeburg, 2008

[7] *Bragin A.P.*; Zaizew W.E.; Melnishuk A.P.; Poltarushnikow S.A.: Grounds and background of research activities in the field of pneomomechanical forming. Journal of aerospace technique and technology, 2007, P. 42, Ukraine

[8] *Steiger E.*: Extracorporal Laser Induced shock wave Lithotripsy (ESWL). Laser in medicine and surgery: journal for application and exploration of laserbeam, Laser Assoc. of Neurolog. Surgeons of Europe; 1987

[9] *Hammann, J.-F.*; *März*, *H.* et al.: Untersuchung zur Stoßwellenerzeugung, Werkstoffbelastung und Technologie beim Hydrospark-Verfahren; BMFT-FB T 76-78; 1974
[10] *Haeusler*, *J.; März, G.*: Optimierung von Drahtexplosionen zum Aufweiten zylindrischer Rohre nach dem Hydrospark-Verfahren; 1968
[11] *Bruno E.J.:* High-velocity forming of metals. American society of tool and manufacturing engineers, Dearborn, Michigan, 1968
[12] *Eguia, I.; Jose, J. S.; Knyazyev, M.; Zhovnovatyuk, Y.*; Pressure Field Stabilisation in High-Voltage Underwater Pulsed Metal Forming Using Wire-Initiadet Discharges. Key Engineering Materials Vol. 473, Sheet Metall, 2011
[13] *Golovashchenko, S.F., Bessonov, N.M., Ilinich, A.M.:* Two-step method of forming complex shapes from sheet metal, Journal of Materials Processing Technology, Volume 211, Issue 5, 1 May 2011, P 875-885
[14] *Homberg*, *W.; Beerwald, C.; Pröbsting, A.:* Investigation of the Electrohydraulic Forming Process with respect to the Design of Sharp Edged Contours. Proceedings ICHSF 2010, Ohio USA
[15] *Homberg, W.; Djakow E. Akst O.:* Some aspects regarding the use of *a* pneumo-mechanical high speed forming process, Proceedings ICHSF 2012, Dortmund, Germany, 25 April 2012
[16] *Homberg, W.; Djakow E.:* The investigation of a pneumo-mechanical high speed forming process; 13th International scientific and technical conference "The Progressive Engineering & Technique" Journal of mechanical engineering (Vesnik) 64, 2012, S. 172-177, Sevastopol, Ukraine
[17] *Homberg, W.; Djakow E.; Akst, O.:* Investigation of a pneumo-mechanical high speed forming process with respect to the forming of complex sheet and tube components; 14th International scientific and technical conference "The Progressive Engineering & Technique". Journal of mechanical engineering (Vesnik) 67, 2013, S. 180-188, Sevastopol, Ukraine
[18] *Knyazyev, M.; Perez, I.; San José, J.; Zhovnovatyuk, Y.*: Pressure Fields Repeatability at Electrohydraulic Pulse Loading in Discharge Chamber with Single Electrode Pair. Proceedings ICHSF 2012, Dortmund, Germany, 25 April 2012
[19] *W. Hartmann, A. Member, J. Kieser, K. Rohde:* The Thermohydraulic Generator – A Pulse Power Source of Intense Pressure Pulses, Erlangen, 2000
[20] *Thewes, R.:* Hydro-Pulseforming-eine vorteilhafte Alternative zum Umformen von Blechplatinen. Hydroumformung von Blechen, Rohren und Profilen. Band 6, Fellbach 2010