

УДК 62-97/-98

Professor Dr. Ing. Homberg W., Dipl. Ing. Djakow E., M. Sc. Akst O.
Chair of Manufacturing and Forming Technology (LUF), "University of Paderborn", Paderborn, Germany
(wh@luf.uni-paderborn.de, ed@luf.uni-paderborn.de, oa@luf.uni-paderborn.de)

INVESTIGATION OF A PNEUMO-MECHANICAL HIGH SPEED FORMING PROCESS WITH RESPECT TO THE FORMING OF COMPLEX SHEET AND TUBE COMPONENTS

Гомберг В. д.т.н., проф., Дьяков Е., Акст О.
Университет Падерборн, г. Падерборн, Германия

ИССЛЕДОВАНИЯ ВЫСОКОСКОРОСТНОГО ПНЕВМОМЕХАНИЧЕСКОГО ПРОЦЕССА ПО ФОРМОВКИ СЛОЖНО СТРУКТУРИРОВАННЫХ ЛИСТОВЫХ И ТРУБЧАТЫХ КОМПОНЕНТОВ

Lightweight design is playing an increasing role in the automotive and aerospace industries due to the stringent emission regulations. Hence it is necessary to produce parts with complex geometries from sophisticated high-strength materials. In this context, and especially when high strength materials have to be formed into highly complex geometries, it is inevitable that new manufacturing processes will need to be developed which meet these requirements. High speed forming processes have a very high potential when it comes to shaping complex, sharp-edged parts and constitute a key means of reducing a component's weight and hence of complying with the stringent emission regulations and also saving on essential resources. These processes and, in this case, pneumo-mechanical and electrohydraulic forming in particular, are a major subject of intense research at the University of Paderborn's Chair of Forming and Machining Technology (LUF). To be able to bring these processes into industrial use, it is necessary to identify the influence of different process parameters on the forming result. This will not only help to optimize the process itself, but will also lead to a better understanding of the process phenomena.

This paper presents recent results relating to the influence of different process parameters, such as the acceleration pressure and the filling level of the working media, on the forming result of sharp-edged, sheet metal parts and square-formed tube geometries in aluminium using a pneumo-mechanical, high speed forming process. It is seen that the forming result can effectively be influenced by varying the acceleration pressure and the filling level. Furthermore, this paper presents the results of basic research conducted on pneumo-mechanical high speed forming and its comparison with conventional hydroforming.

Keywords: Pneumo-mechanical forming, High speed hydroforming, Sheet metal forming, Tube forming, Hydroforming

Introduction

The protection of the environment and resource saving are becoming increasingly important in manufacturing industry as a whole, and especially in the automobile and aerospace industries. Several recent research projects have thus been aimed at implementing lightweight concepts in production, using innovative materials and complex part designs with an enhanced functionality. In addition to material development, it is also necessary to develop new, innovative production processes which are able to meet the requirements for shaping new materials like high strength steels into highly complex geometries, as well as permitting the integration of additional process steps like cutting or joining while, at the same time, being highly cost and energy effective.

In this context, high-speed-forming processes have a high potential for meeting these requirements. As the forming speed and the media pressure are very high by comparison to conventional stamping processes, such as deep drawing or quasi-static hydroforming, the materials show improved formability, thus enabling conventional forming limits to be significantly exceeded in a positive manner. This makes it possible to create very sharp-edged and complex geometries by forming. [2]

The technology of high speed forming has been familiar since the 19th century already and was intensively examined in the United States, Germany and the Soviet Union up to the 1950s [1] when explosives and both electrohydraulic and pneumo-mechanical pressurization [1-4] were used to form workpieces either in a die or freely. High-speed forming includes all the manufacturing processes that release the necessary forming energy very quickly and transfer it to the workpiece in a time range from a few microseconds to 1000 microseconds.

This paper presents recent research results from pneumo-mechanical high speed forming (PMF), where a plunger is accelerated through a tube, by means of compressed air, into a forming die that contains a working medium like water. Both the collision and the immersion of the plunger into the working medium create very high pressures over a very short time, which are used to form the workpieces in a die. The influence of process parameters such as the

acceleration pressure and the filling level of the media on the forming result is shown in this paper, together with a comparison of conventionally formed parts with parts formed by PMF.

Research objective

Current research at the Chair of Forming and Machining Technology (LUF) is focused on fundamental investigations of high speed forming processes, and especially of pneumo-mechanical (PMF) and electrohydraulic forming (EHF). These investigations are to provide an overview of different process parameters and their influence on the forming result as well as their interaction with each other. This will lead to a better understanding of the process phenomena and will highlight the potential for boosting the effectiveness of these.

In the case of pneumo-mechanical high speed forming, key process parameters include the acceleration pressures, the acceleration height, the working media type and its filling level, and also the tool clamp forces. The influence of the acceleration height, the working media type and the tool clamp forces was described in [6] and [7]. This paper deals with the influence of the acceleration pressure as well as with the filling level of the working media. Knowing the main process parameters and their influence on the forming results, it is possible to ensure that the process is more efficient and make it available for industrial use. A comparison of the forming result achieved by conventional forming processes and high speed forming will highlight the potential that high speed forming has by comparison to conventional forming processes. In addition to the sole use of PMF, it would also be conceivable to extend conventional forming processes by high speed processes and thus to be able to form more complex, multifunctional parts.

Experimental setups and measuring procedure

The experiments were performed on a pneumo-mechanical setup consisting of a pressure generation unit, a vertically arranged acceleration tube and a forming die (Figure 1). Inside the tube, a plunger is accelerated by compressed air and dives into the water-filled chamber, thereby generating very short pressure pulses of up to 60 MPa, forming sheet metals or tubes in a die.

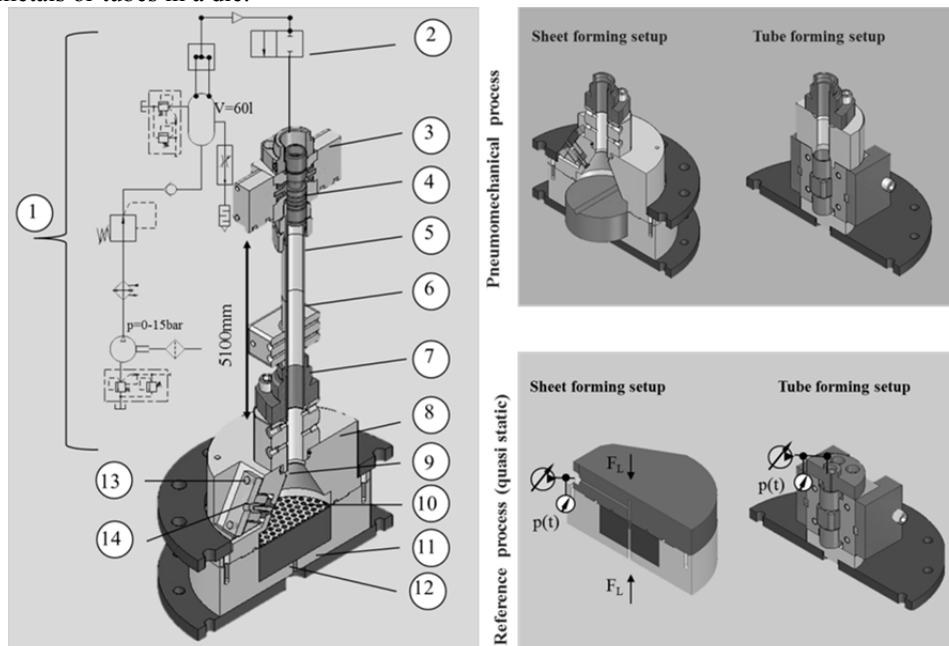


Fig. 1. Pneumo-mechanical setup: 1 – pressure generation unit; 2 – lever valve; 3 - release mechanism; 4 – plunger; 5 – acceleration tube; 6 – light barrier; 7- SAE-flange; 8 - pressure chamber; 9 – working medium; 10 - membrane pressure gauge (die); 11 - lower tooling adaptor; 12 – vacuum connection; 13 – sensor adaptor; 14 – pressure transducer (PCB 109C11 $p=0-5500$ bar)

The maximum acceleration pressure 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 tube is a device for measuring the plunger's speed, which can provide information on the plunger's energy. The pressure measurements inside the tool were performed using a high-frequency ICP pressure sensor (109C11) from PCB, New York, USA. The recording of all the measured signals was performed by a four channel digital oscilloscope from Agilent Technology 1000. The measurement of the forming level was made using a coordinate measuring machine (Contura G2) from Zeiss, Oberkochen, Germany, and the part geometry was defined by the optical 3D forming analysis system, Argus, from GOM, Braunschweig, Germany.

In addition to the pneumo-mechanical setup, conventional quasi-static hydroforming setups were used as a reference process for the comparison of conventional and high speed forming processes. A sheet and tube tool setup consisting of a two part forming die, intermediate or clamping plates and pressure intensifier ($p_{\max} < 400$ MPa) was used to this end, for more details see also [5]. To apply the necessary locking force, the tool for sheet forming was mounted inside a 8000 kN hydraulic press. The sealing for both processes was reliably achieved by using of a simple O-ring (70 shore hardness) and a 1mm knife-edged ring.

Results and discussion

The focus of this work is on analysing the influence of different process parameters such as the filling level and the acceleration pressure on the forming result, with the aim of making the process more efficient and comparing pneumo-mechanical high speed forming with conventional forming processes, like quasi-static hydroforming. This will make it possible to work out the different potentials and properties of PMF by comparison with conventional hydroforming. The chosen demonstrator geometries were a V-shaped groove with a wall angle of 90° and a width of 15 mm for sheet metal forming and a rectangular shape of 41x41 mm with a height of 40 mm for tube forming. These geometries have only minimal acceptable geometry deviations, and the small radius on the V-shaped geometry, in particular, is very hard to form by quasi-static forming processes but can easily be produced by high speed forming processes and thus provides an opportunity to highlight the possibilities of PMF.

Comparison of sheet metal forming by pneumo-mechanical high speed and hydroforming processes

To achieve better characterization of the potentials of PMF and quasi-static hydroforming, a qualitative comparison was performed, using a membrane as the forming die, in order to analyse the planar pressure distribution on a sheet metal part. Furthermore, a V-shaped part geometry was employed so as to represent a complex sharp-edged part, like a modern car body element. While the pressure distribution on the sheet metal was very homogeneous in both processes, and its reproducibility was even very good, see also [6], the sharply contoured workpiece can be produced more conveniently by the pneumo-mechanical process than by quasi-static hydroforming.

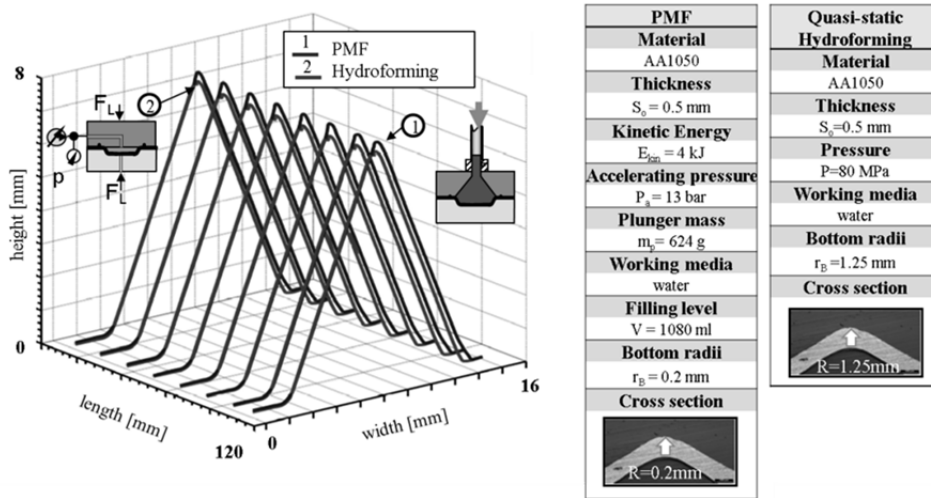


Fig. 2. Manufacture of a sharply contoured geometry by pneumo-mechanical high speed forming and conventional hydroforming

Comparing the formed parts produced by these two methods, the difference in the forming level was less than 2%. But one key aspect is that, while pneumo-mechanical forming achieves bottom radii of $r_B = 0.2 \text{ mm}$, which is smaller than the initial blank thickness of 0.5 mm, quasi-static hydroforming only achieves radii of $r_B = 1.25 \text{ mm}$ (see Figure 2). Nevertheless, quasi-static hydroforming showed a lower deviation of 60 μm over the whole length of 105 mm, compared to 80 μm for pneumo-mechanical forming. The experimental investigation was conducted on aluminium (AA 1050) blanks with an initial thickness of 0.5 mm.

During the experiments, it was found that, under specific conditions, the plunger collides with the blank, destroying the surface of the blank and thereby making the blank unusable. There are several ways of preventing this collision – for example, using a working medium with a higher density or non-Newtonian fluids (e.g. water with starch) or an elastic membrane [6, 7] as well as increasing the filling level of the medium. To ensure comparability with quasi-static forming, it was not possible to use a different medium or a membrane, which is why the filling level was increased. Experiments showed that an increase in the filling level of up to 30 % has no influence on the uniformity of the pressure distribution but does affect the forming level and prevents the plunger from colliding with the blank.

Due to the very short duration of the forming process of approximately 2 ms, the eightfold screw connection on the pneumo-mechanical tool is enough for applying a sufficient closing force, while the tool for the quasi-static hydroforming process has to be closed and kept shut by an expensive press, which is not necessary in this case.

Further investigations into the influence of process parameters such as plunger mass, the consistency of several working media and the filling level are the subject of current research work at the LUF.

Comparison of tube forming by pneumo-mechanical high speed forming and hydroforming

Additional research work is focused on a detailed analysis of the influence of process parameters, such as the filling level and the acceleration pressure, for the forming of tubes into a square-shaped geometry using PMF (see Figure 3). This geometry was further employed for a comparison of PMF and quasi-static hydroforming, since it is a highly complex geometry to form with quasi-static processes without the use of axial forces to push more material into the major forming zone.

Influence of the filling level. As mentioned above, previous work revealed an influence of the filling level on the forming result during pneumo-mechanical sheet metal forming. Based on this knowledge, further experimental investigations looked into the influence of the filling level on the forming results achieved with pneumo-mechanical tube forming (see Figure 3). The first experiments using a filling level of 50 ml of pure water revealed hardly any forming of the tube, on account of the very high impact speed of the plunger and hence the higher water splashes, because there was not enough medium to fill the major forming zone after the splashes had occurred. Increasing the filling level up to 100 ml leads to more pronounced tube formation and decreased edge radii. But, unfortunately, this quite good forming result was associated with the occurrence of cracks in the corner region and a higher geometrical deviation of up to 1 mm over the entire length of 105 mm. A rise in the filling level to above 100 ml (minimum level) makes it possible to achieve edge radii of $r_e = 10$ mm with a lower geometrical deviation of $90 \mu\text{m}$ in the edges and also in the forming level. To conclude, it can be stated that a minimum filling level is absolutely necessary for the homogeneous and efficient forming of tubular geometries.

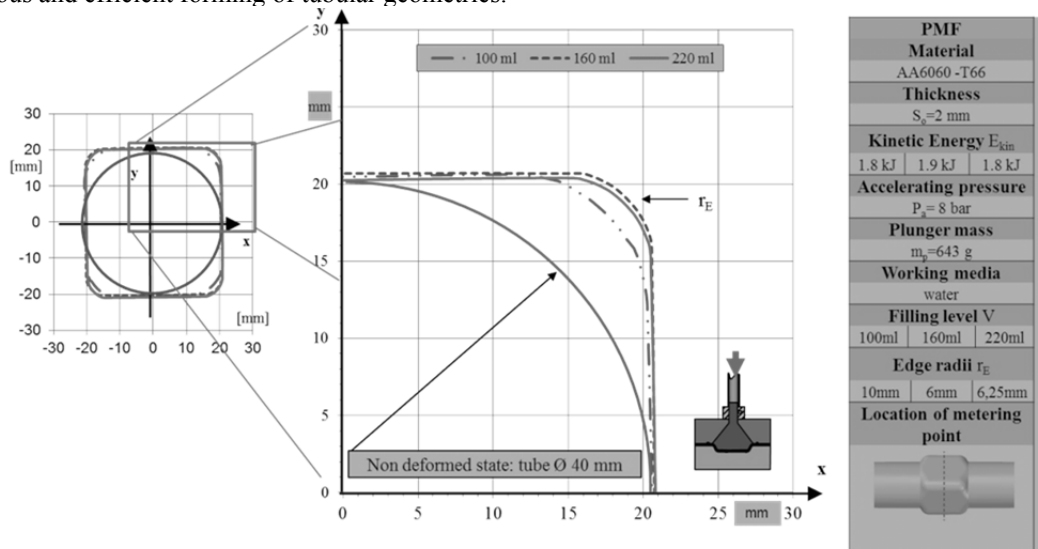


Fig. 3. Influence of the filling level on tube forming

A further increase in the filling level of 60 % leads to 40 % smaller edge radii ($r_e = 6$ mm) compared to the radii achieved with a minimum level of 100 ml ($r_e = 10$ mm). A further increase in the filling level from 60 to 120 % has no further effect on the forming result ($r_e = 6$ mm) in the radial and axial direction; the geometrical deviation is less than 2% compared with the forming result using 100 ml (see Figure 3).

The experiments were performed with an acceleration pressure of 8 bar and virtually identical kinetic energy on tubes of aluminium (AA 6060 T66) with an initial thickness of 2 mm. Future research work at the LUF will involve investigations into the optimum filling level as a function of the acceleration pressure or kinetic energy, the establishment of the filling level in different working media and also the reduction of these deviations and further investigations into the influence of process parameters on the microstructure or part surface.

Influence of the acceleration pressure and pressure level. Due to the fact that the plunger is accelerated during the free fall, it is obvious that the acceleration pressure has an influence on the kinetic energy and hence on the course and result of pneumo-mechanical forming. Hence, different acceleration pressures (2, 4 and 8 bar) were used to analyse this influence on the forming level and on the quality of the part. To demonstrate the potential of pneumo-mechanical high-speed forming, these experiments were compared with corresponding results produced by quasi-static hydroforming, without any axial pushing of the material to be formed (see Figure 4).

An analysis of the formed geometry using the coordinate measuring machine shows that an acceleration pressure of 2 bar results in a comparable formed geometry to that achieved with quasi-static hydroforming for radii of 16 mm at a forming pressure of 45 MPa (see Figure 4). A further increase in the acceleration pressure from 2 to 8 bar leads to smaller radii ($r_e = 6$ mm) in the corners and a wider square shape of 41 mm x 41 mm. The hardness distribution on the formed part increases by up to 15 % to 92 HV, being nearly the same in the radial and axial direction.

Especially at higher acceleration pressures, 20 % of the kinetic energy is dissipated by the air resistance and friction in the tube during this process, contrary to the case in the theoretical observations. A higher energy is thus needed to achieve a higher level of forming than that calculated theoretically. Reducing this wastage, plus further investigations into the influence of process parameters on the microstructure, is the subject of current research work at the LUF.

Analyses of the thickness distribution employing both forming analysis (GOM ARGUS) and measurements under microscopes of parts produced by PMF that have undergone maximum deformation show a non-uniform thickness distribution from the middle of the square area towards the corners in the axial direction.

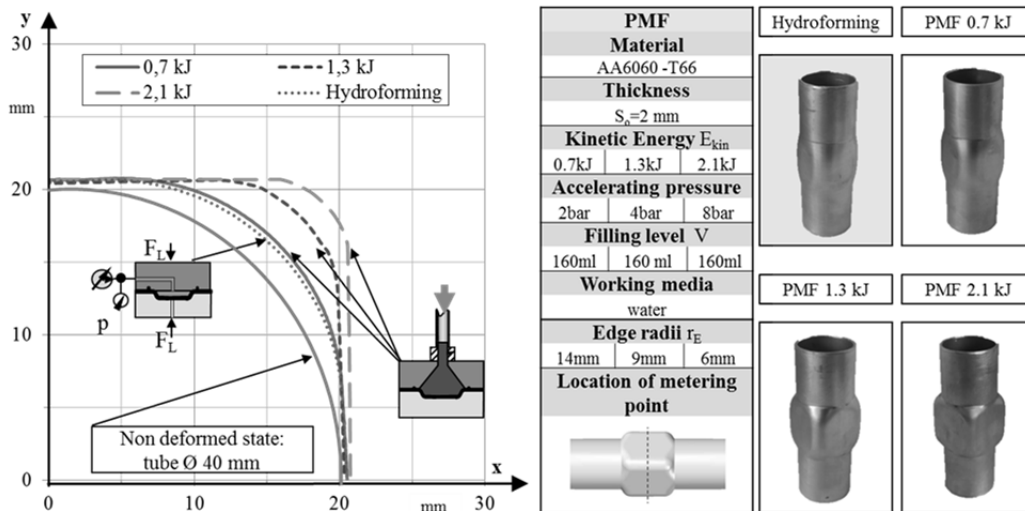


Fig. 4. Influence of acceleration pressure on tube forming

The highest thickness variations obviously result in the centre of the square area, at 22 %, and extend diagonally to the outer corners, showing a 16 % decrease in thickness there (see Figure 5). The behaviour of the strains in the part can be assumed to be the same. This phenomenon was confirmed by overload tests using very high kinetic energies of 2.8 kJ, aimed at failure of the parts, which proved that cracks occurred mostly in the centre of the square area and/or in the corners. A comparison of the analysis results obtained from the forming analysis and the measurement under a microscope showed a deviation of 3.25%, which was seen to be identical.

Further experiments using PMF showed not only a fairly uniform pressure distribution but also good repeatability. The reproducibility of the forming level and the achievable edge radii employing identical parameters was less than 3%. Reducing the thickness deviations and developing improved process strategies is subject of current research work at the LUF.

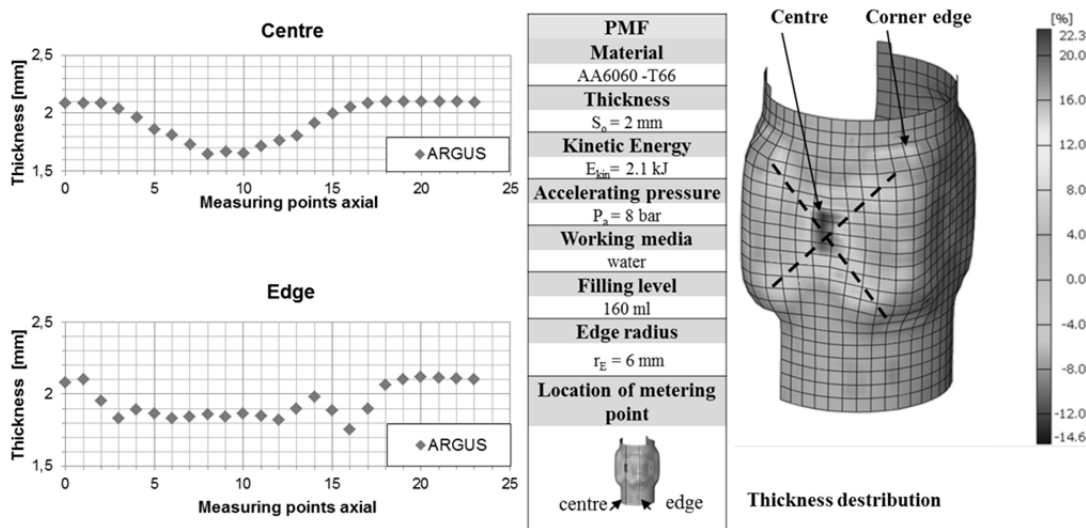


Fig. 5. Thickness distribution in the axial direction

Conclusion

1. A comparison was performed of the forming results produced by pneumo-mechanical high speed forming and quasi-static hydroforming. It was shown that sharply contoured workpieces can be more conveniently manufactured by pneumo-mechanical high speed forming. Furthermore, pneumo-mechanical processes achieve 80 % sharper edge radii and a 20-40% higher forming of sheet metal and tubular components than quasi-static hydroforming.
2. It could be shown that that a minimum filling level is absolutely necessary for the homogeneous forming of sheet metal and tubular geometries.
3. Furthermore, the results show that a certain increase of filling level (up to 60%) allows higher degrees of deformation.
4. Moreover, pneumo-mechanical high speed forming shows highly homogeneous hardness distributions in the radial/axial direction and provides a very high repeatability for the selected part geometry.

Анотація. У зв'язку з суворими нормами викиду вуглекислого газу і економії ресурсів в автомобільній і аерокосмічній промисловості усе більш вирішальну роль грають полегшені конструкції. Таким чином, на сьогоднішній день необхідність виробництва конструкцій із складною геометрією з високоміцних матеріалів є високоактуальною. У цьому плані, неминуха розробка нових процесів для високоміцних матеріалів тих, що відповідають вищевикладеним вимогам. Процеси високошвидкісного формування показують більш високі показники відносно формування комплексних гострокрайових деталей і є важливим ключем до зниження ваги компонентів, при цьому відповідаючи високим вимогам викиду вуглекислого газу, а також сприяючи збереженню важливих природних ресурсів. Дослідження пневмомеханічного і електрогідравлічного процесу формування металу є важливим предметом інтенсивної дослідницької роботи кафедри формування і обробки технологій університету Падерборн. Для інтеграції вказаних процесів в промисловості, дуже важливе визначення впливу різних параметрів процесу на формування результату, який не лише сприяє оптимізації самого процесу, але і призводить до кращого розуміння явищ цих процесів.

У статті розглядається вплив прискорення стислого повітря і рівня заповнення робочого середовища на формування деталей з листової і трубчастої геометрії. Досвідченим шляхом була встановлена можливість виготовлення складних гострокрайових і квадратоподібних геометричних деталей з алюмінієвих сплавів за допомогою пневмомеханічного штампування. Результати дослідження роблять явним факт ефективного впливу тиску стислого повітря і рівня заповнення камери тиску, що змінюється, на формування деталей. У цій роботі представлені результати ґрунтовних досліджень пневмомеханічного штампування в порівнянні з конвенціональним гідроформингом.

Ключові слова: пневмомеханічне штампування, гідроформинг, формування листового металу, формування труб

Аннотация. В связи со строгими нормами выброса углекислого газа и экономии ресурсов в автомобильной и аэрокосмической промышленности все более решающую роль играют облегченные конструкции. Таким образом, на сегодняшний день необходимость производства конструкций со сложной геометрией из высокопрочных материалов является высокоактуальным. В этом плане, неизбежна разработка новых процессов для высокопрочных материалов отвечающих вышепоставленным требованиям. Процессы высокоскоростной формовки показывают более высокие показатели относительно формирования комплексных острокраевых деталей и являются важным ключом к снижению веса компонентов, при этом соответствуя высоким требованиям выброса углекислого газа, а также способствуя сохранению важных природных ресурсов. Исследования пневмомеханического и электрогидравлического процесса формовки металла является важным предметом интенсивной исследовательской работы кафедры формирования и обработки технологий университета Падерборн. Для интеграции указанных процессов в промышленности, очень важно определение влияния различных параметров процесса на формирование результата, который не только способствует оптимизации самого процесса, но и приводит к лучшему пониманию явлений этих процессов.

В статье рассматривается влияние ускорения сжатого воздуха и уровня заполнения рабочей среды на формирование деталей из листовых и трубчатых геометрий. Опытным путем была установлена возможность изготовления сложных острокраевых и квадратнообразных геометрических деталей из алюминиевых сплавов при помощи пневмомеханической штамповки. Результаты исследования делают очевидным факт эффективного влияния изменяющегося давления сжатого воздуха и уровня заполнения камеры давления на формовку деталей. В данной работе представлены результаты основательных исследований пневмомеханической штамповки в сравнение с конвенциональным гидроформингом.

Ключевые слова: пневмомеханическая штамповка, гидроформинг, формовка листового металла, формовка труб

REFERENCES

- [1] Wilson, F.: High Velocity Forming of Metals. Prentice-Hall International, London, 1964
- [2] Lange, K.; Müller, H.; Zeller, R.; Herlan, Th.: Hochleistungs-, Hochenergie-, Hochgeschwindigkeitsumformung. In: Lange, K. (Hrsg.): Umformtechnik – Handbuch für Industrie und Wissenschaft, Bd. 4: Sonderverfahren, Prozesssimulation, Werkzeugtechnik, Produktion, Springer-Verlag, Berlin 1993.
- [3] Tominga, H.; Takamatsu, M.: Hydropunch, a pneumatic-hydraulic-forming machine. 2nd 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] 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
- [6] 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
- [7] Homberg, W.; Djakow E.: The investigation of a *pneumo-mechanical high speed forming process*; 13th International scientific and technical conference "The Progressive Engineering & Technique" 11-15 June 2012, Sevastopol, Ukraine
- [8] Vovk, V.; Taran, V.; Vovk, A.: Grundlagen für das Hydro Impuls Umformen von Blechen, Abschlussbericht zum DFG-Schwerpunktprogramm SPP1098, Shaker Verlag, Aachen, 2006
- [9] Vovk, V.; Taran, V.; Vovk, A.: Effects of Hydro-Impulse forming of Blanks. Steel Research 7, 2005No. 12 P.140-143
- [10] Neugebauer R. Seifert, M.: Internal high-pressure forming of light metals, ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb, Volume 100, Issue 9, September 2005, Pages 481-489