Development of a Pneumatic High-Speed Nakajima Testing Device[*]

M. Engelhardt[1], H. von Senden genannt Haverkamp[1], C. Klose[1], Fr.-W. Bach[1]

[1] Institute of Materials Science, Leibniz University Hannover, Germany

Abstract

Forming limit diagrams are an essential tool for describing the formability of sheet materials in the deep-drawing process. Here, the well known and frequently employed procedures are the Nakajima and the Marciniak-Tests. Whereas these procedures' standardisation is quite advanced in the quasi-static range, numerous different test procedures exist in the range of elevated forming speeds. In the first part of this work, an overview of the various procedures is given for generating forming limit diagrams in the high speed range. In the second part, a pneumatically operated testing device is introduced which was developed at the Institute for Material Science for performing Nakajima-Tests in the high speed range. Using this device, standard specimens can be dynamically formed according to the Nakajima-Test. The testing device is to be employed for scientifically exploring the deformation mechanisms operating at very high forming speeds. The testing device's mode of functioning is demonstrated by means of forming discs of an EN AW-6082 aluminium alloy sheet. In doing this, the testing apparatus is mainly characterised by holding the testing conditions constant during the tests: This particularly concerns the velocity of the tool for forming the sheet discs.

Keywords

Forming Limit Diagram, High-speed Nakajima Test, Aluminium Alloy EN AW-6082

---

[*] *This work is based on the results of Paketantrag 343 "Entwicklung einer Methodenplanung für die Hochgeschwindigkeitsblechumformung ": The authors would like to thank the German Research Foundation (DFG) for its financial support.*

1 Introduction

Using a broad spectrum of materials, it has been possible in the past to show the favourable influence of high-speed forming on the formability of various materials [1]. Apart from an increase in the yield point, both steel materials as well as lightweight metals demonstrate an improved formability [2] [3]. Combining quasi-static and dynamic forming additionally extends the process limits [4]. To explain these effects, it was necessary to develop suitable testing devices with which to be able to specifically investigate the responsible mechanisms using material science experiments.

2 State of the art

Hitherto, different testing devices were developed in order to experimentally modify the high-speed forming. An overview of various equipment designs is given in the following section. Here, the different testing devices are subdivided according to type how the energy is supplied for open sheet forming (in cases of dieless forming) or the punch (in cases of die forming).

2.1 Explosive forming

One of the first comprehensive articles giving an overview for determining the parameters during high-speed sheet forming already originated in 1967 [1]. The procedures were subdivided with respect to the detonation speed. Here, the forming only depended on the formation of a shock wave during the employment of high-explosives or on a stepwise increase in pressure.

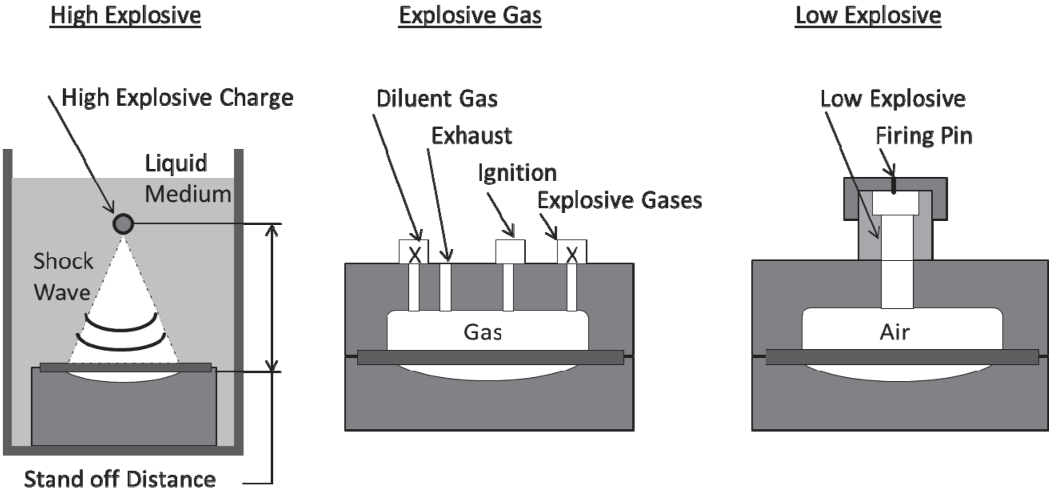

***Figure 1**: Explosive forming [1]*

The different arrangements are depicted in Figure 1. On employing high-explosives, depicted here on the left, an open system is used, whereas in the two other cases, the test set-up is completely closed. Besides this, compressible working media are used here. The strain rates, which attain approx. 10^4 1/s, depend on the working medium, explosives and specimen material. The detonation velocities can reach approx. 300 m/s to 7,500 m/s.

2.2 Electromagnetic forming

If electromagnetic forming is employed to determine the parameters, then two variants can be differentiated: Either free forming or forming into or over a tool, as can be seen in Figure 2 [5] [6]. Apart from the material parameters, the tendency for forming creases is also investigated when using this arrangement [5]. Here, the use of different specimen geometries is theoretically possible so that the ratio or the major and minor forming strains can be varied accordingly.

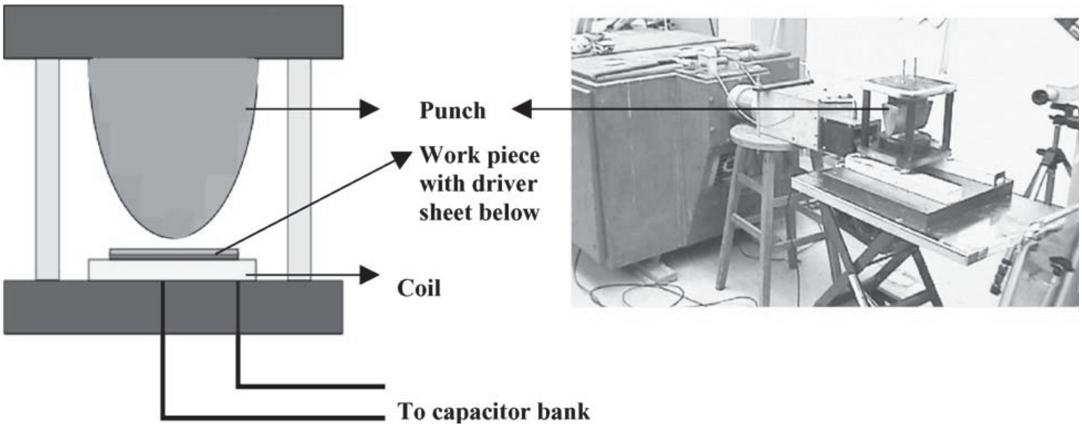

Figure 2: Electromagnetic forming using a die [5]

Using the testing device described here, the sheet is deformed using speeds of 50…220 m/s and strain rates of the order of approx. 10^3 1/s [5]. The strain distribution is evaluated by using a dot-matrix printed on the specimen's surface. The forming can not be specifically interrupted during the occurrence of the first crack. Apart from explosive forming, electromagnetic forming is the most important process for high-speed forming. Thus, if one wants to determine the material parameters, the testing devices described here provide the possibility of doing this by using the same procedure with which the components are manufactured. Accordingly, the best experimental adjustability is possible in the case of an electromagnetic forming procedure.

2.3 Pneumatic forming

A tool operated by means of compressed air is introduced in [7] which, however, was not specially developed for determining FLD's but for investigating stamping processes. The tool, which operates using a working pressure of 8 bar, was designed to be integrated into conventional presses. The set-up is schematically shown in Figure 3. The three nested compression steps can be identified, which sequentially compress the air and accelerate the tool's punch. In a mechanically operating press, using 400 kN compression force at an operating power of 4 kW and a maximum press velocity of 0.14 m/s, it was possible to obtain maximum punch speeds of 13.66 m/s. Here, the punch's maximum impact energy is approx. 1400 J. Using this arrangement, it was possible to form sheets of structural steel having a maximum thickness of 10 mm with a punch diameter of 30mm.

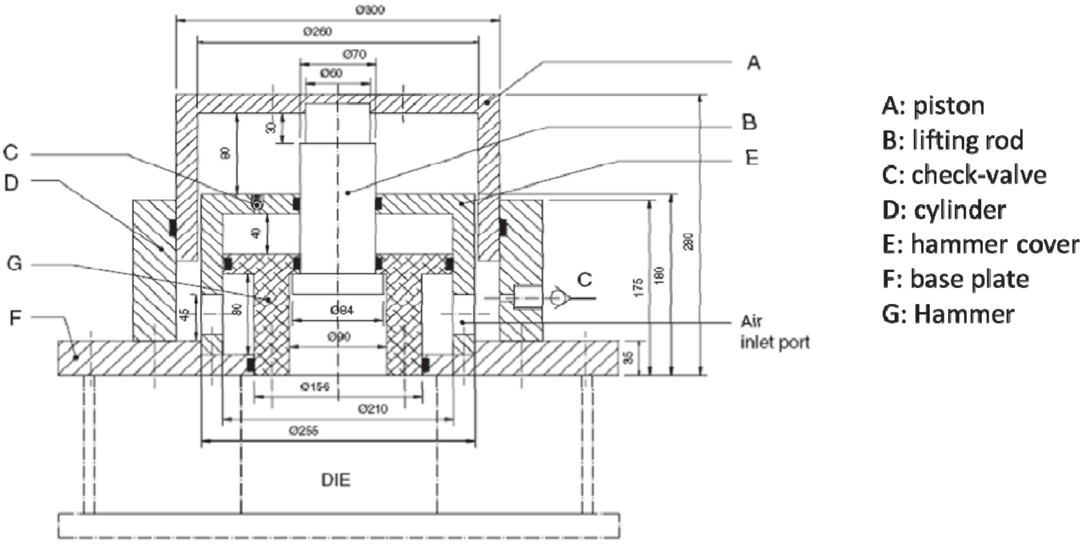

***Figure 3**: pneumatic testing device according to [7]*

2.4 Hydraulic forming

An hydraulically operated testing device is described below and depicted in Figure 4 with which both free forming as well as tool forming can be carried out by means of a shock wave in a medium; in this case water. Here, the piston is accelerated by the High Pressure Driver through an evacuated region and strikes the water's surface. The water section is here separated from the vacuum section by means of a diaphragm in order to avoid boiling the water. In the test section, the resulting compression wave impacts a sheet disc, which seals the tube, and deforms the disc.

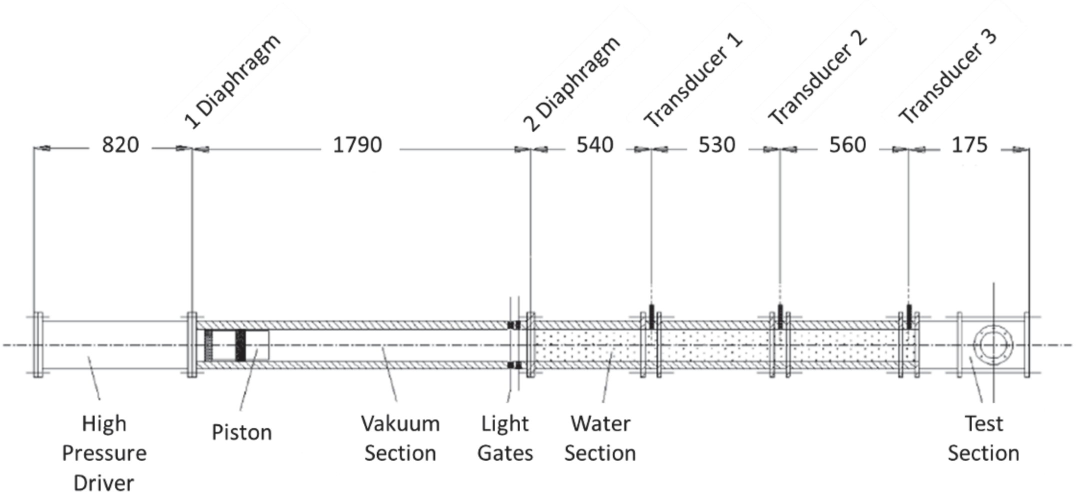

***Figure 4**: Hydraulic testing device according to [8]; View turned through 90° to the left*

On impact of the shock wave, pressures of up to 60 MPa are produced within a few micro-seconds. Using this equipment, it was possible to achieve forming displacements of up to 20 mm in copper sheets of thicknesses 0.55... 1.5 mm. The sheets' deformation rate is here between 50.9 m/s and 95.5 m/s. The rate was measured using a high-speed camera and illuminating the test set-up through a window in the test section from an external source. The observed strain rates varied between 200…2700 1/s.

2.5 Mechanical forming

The Nakajima-Test is described in [9] with the aid of a testing device modified for Crash-Tests and depicted in Figure 5. The device is 10 m long, 1.4 m wide and consists of four components: an hydraulic unit for the acceleration, a sledge which is guided by rails, a forming tool for the Nakajima-Test and a shock-absorbing unit. The forming tool comprises of a base plate, a drawing ring and a hemispherical punch analogous to the quasi-static Nakajima-Test. A characteristic feature here is that the forming can not be stopped when the first incipient crack is initiated, which is usual for the quasi-static Nakajima-Test. The necessary deformation for crack formation was assumed in analogy to the quasi-static test and the punch's penetrating depth is accordingly limited.

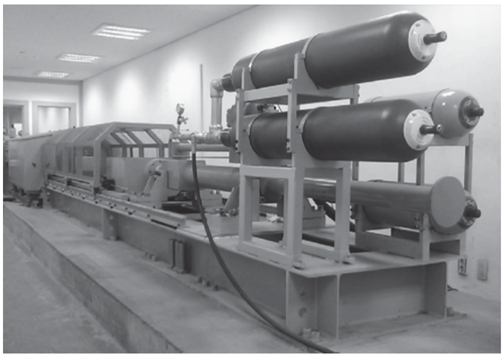

***Figure 5**: Mechanical testing device according to [9]*

The sledge has a weight of 290 kg and is accelerated to a maximum speed of 21 m/s. Forming speeds of 2.3....10 m/s were used for the tests described in [9]. This produced strain rates of approx. 100 1/s. The punch used had a diameter of 100 mm. 245 mm diameter discs having a web width of 20 ... 100 mm as well as complete specimens were tested. The punch's forming displacement was limited to 20 mm. The lubricating media used was Teflon, Teflon combined with Vaseline as well as Teflon and plasticine.

A mechanical testing device based on a drop tower is described in [10] and is depicted in Figure 6. Again the Nakajima-Test according to EN ISO 12004-2 forms the basis of this test. Sheet discs are formed by a hemispherical punch. The punch is accelerated by the drop-weight of the drop tower and pressed through the metal sheet. In doing this, the punch's penetration depth is mechanically limited by the base. Besides the base plate, the pressure ring and the punch, the tool consists of a very solid frame construction which absorbs the drop-weight's impact and transmits the energy into the base plate. For a maximum drop-height of 12 m and a drop-weight of 300 kg, drop-speeds of up to 12.5 m/s can be obtained. This leads to a strain rate of approx. 10^3 1/s. Tests were performed using a maximum drop-height of 3 m and a drop-weight of 90 kg. Nakajima-Tests were carried out on 100 mm diameter sheet metal discs using a total of four different geometries. Here, it is also not possible to end the test following cracking. Analogous to [9], the punch displacement is limited to a maximum of 25 mm and the forming is thereby terminated

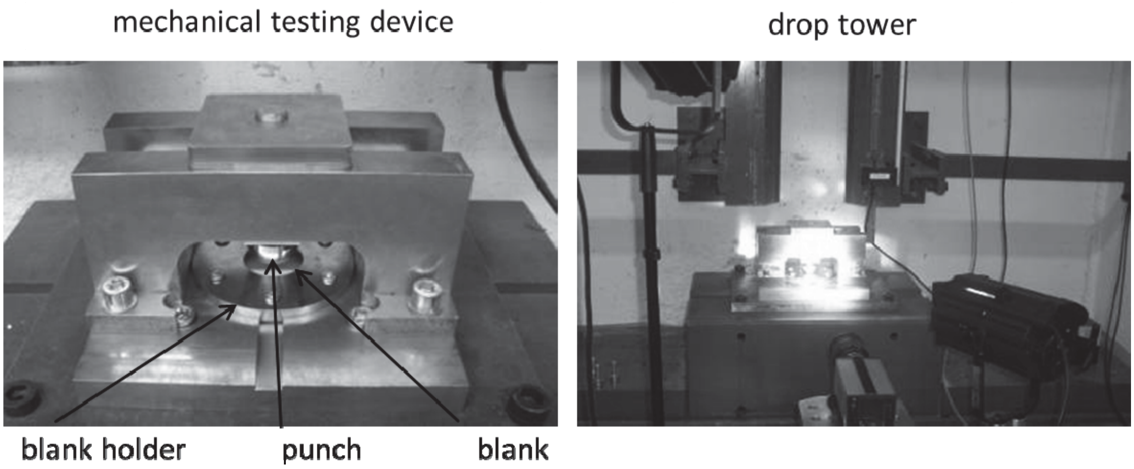

***Figure 6**: Mechanical testing device according to [10]*

2.6 Further methods

Different approaches exist for varying and combining the previously shown procedures.

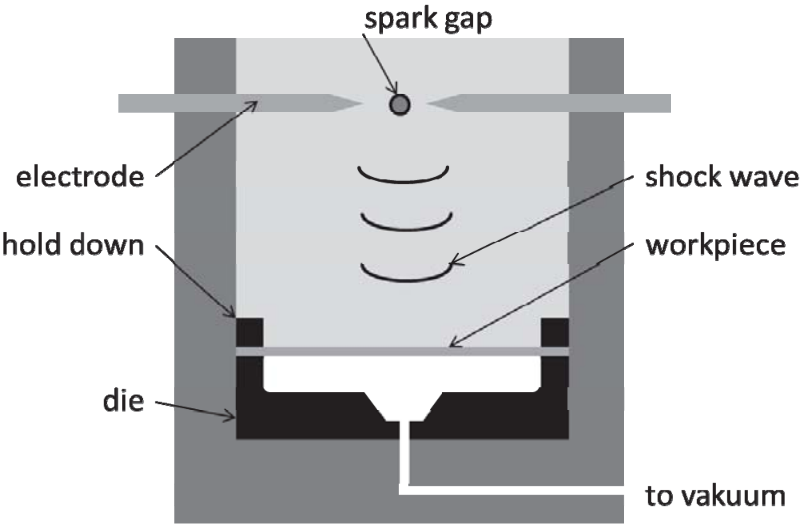

***Figure 7**: Combined forming according to [11]*

An example of a combined procedure is electro-hydraulic forming which is introduced together with other procedures in [11] and is schematically depicted in Figure 8. Here, an electric arc is struck between two electrodes in a surrounding medium; e.g. water. The water abruptly vaporises and produces a shock wave which forms the workpiece. In doing this, the procedure's mode of operation is very similar to that of the explosive forming already described. Both free forming as well as forming into a die can be carried out. The process can be assisted by means of creating a vacuum on the side remote from the operating medium in order to prevent a deceleration due to the build-up of pressure.

2.7 Concluding assessment of the different procedures

Advantages of the explosive forming are very high attainable speeds and strain rates. Disadvantages are the frequent difficulties in sealing the equipment. Owing to the explosives used, the testing is hazardous and therefore high industrial safety requirements must be fulfilled.

For free and closed-tool electromagnetic forming, very high speeds and strain rates can be attained. This is the only procedure with which electromagnetic forming processes can be directly adjusted. Here, constant testing conditions are also difficult to guarantee. Moreover, no defined forming operations frequently take place during free forming.

Generally, pneumatic and hydraulic testing devices have a comparatively simple construction; here, sealing problems can also occur. The forming process is uncertain if no punch is used. If integrated complete specimens have to be used, which are a part of the equipment's sealing, it is not possible to vary the major and minor strain levels.

Mechanical testing devices are comparatively simple and non-hazardous. It is possible to vary disc-shaped geometries and thus the major and minor strain levels. However, very high speeds and strain rates can not be obtained.

Combined procedures can only partially compensate the disadvantages described above.

Table 1 comparatively summarises the described testing procedures and emphasises that no universal procedure exists for all speeds and strain rates.

Principle	Specimen geometry	Strain rate, V_{max}	Source
Explosive	Limited	approx. 10^4 1/s	[1]
Electromagnetic	Limited	approx. 10^4 1/s	[2][4][6]
Pneumatic	No limitation	approx. 10^3 1/s	[3]
Hydraulic	Limited, integrated specimens	approx. 10^3 1/s	[4]
Mechanical	No limitation	approx. 10^3 1/s	[5][10]

***Table 1:** Comparison of different high speed testing setups*

3 Development of a pneumatic testing device for high-speed forming of sheet metal

3.1 Equipment's mode of operation

The maximum height of the drop tower limits the punch speed to a maximum of 10 m/s. A further increase in the punch's speed was not possible using this equipment. However, as mentioned above, the obtainable strain rates were not sufficient. In addition to this, the unfeasibility of thermographic imaging required the equipment's technology to be further developed.

A pneumatic high pressure cylinder was selected for the propulsion. With respect to this, a standard compressed air cylinder with 200 or 300 bar served as the energy source. The necessary working pressure in an intermediate storage vessel can be set via a pressure controller. The equipment is activated via a manual 2/2-port directional valve which opens the compressed air supply from the intermediate vessel to a special rapid switching valve. The valve opens within 50 ms and closes automatically after a further 50 ms. This prevents excessive pressure loss and thus reduces the air volume which is necessary for each test.

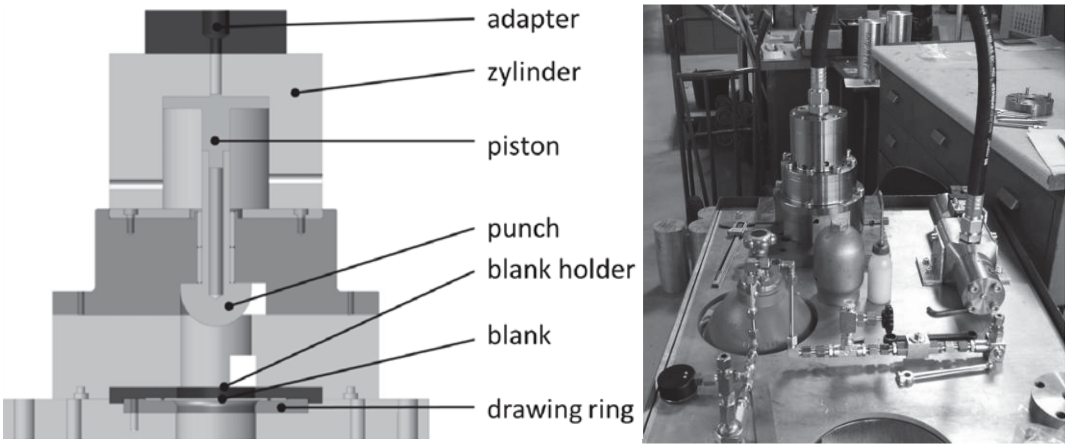

Figure 8: *Schematic drawing (left) and the testing device's layout (right)*

The rapid switching valve is connected to the testing equipment via a high pressure hose. Figure 4 shows the equipment's layout. The cylinder is supplied with compressed air via an adaptor plate, which is connected to the high pressure hose. In its initial condition, the piston, which is connected to the punch, butts against the upper wall of the cylinder. Here, the punch is held by a shear pin (not depicted). As soon as the pressure on the piston surface and the generated punch force exceeds the pin's strength, the pin shears and the piston together with the punch is released. When the piston moves downwards, the piston’s entire surface is pressurised and the punch experiences a forceful acceleration. This type of release guarantees the complete build-up of pressure prior to the piston's movement and maximises the punch's acceleration. Furthermore, the operating piston force and piston acceleration can be varied by means of changing the pressure in the intermediate vessel. Ventilation holes at the end of the cylinder prevent a build-up of back pressure in the lower region of the cylinder and minimise the force acting on the piston after performing the test.

3.2 Tests

Using the testing device described above, 1 mm thick specimens of EN AW-6082 aluminium alloy were formed. Figure 9 shows a 100 mm diameter specimen having a web width of 15 mm following the forming.

A total of 5 geometries having web widths of 15 ... 55 mm were used. The forming was carried out using a 50 mm diameter hemispherical punch. Self-adhering Teflon film was applied to the specimen for the lubrication. The punch's speed was recorded using an optical laser together with a measuring system of the type opto CONTROLL, made by the company MicroEpsilon. Here, the recording frequency was 100 kHz. The maximum operating pressure was 150 bar. The time frame, in which the punch was pressurised, was limited to 50 ms.

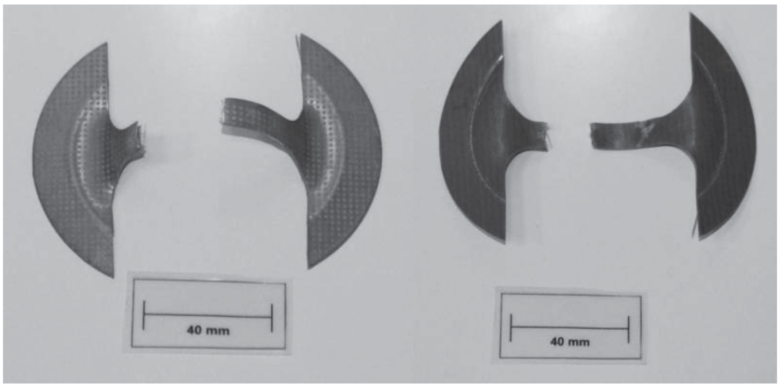

***Figure 9**: Specimen after testing at 150 bar/ 10.9 m/s*

It can be seen that the specimen was not just tested up to incipient cracking, but up to complete rupture. Although the punch's penetration depth can be varied, it is not currently possible to automatically stop the test during the formation of an incipient crack on the specimen's surface. Rupture takes place off-centre. This indicates insufficient lubrication. It was possible to reliably suppress the material's subsequent flow as well as the formation of creases.

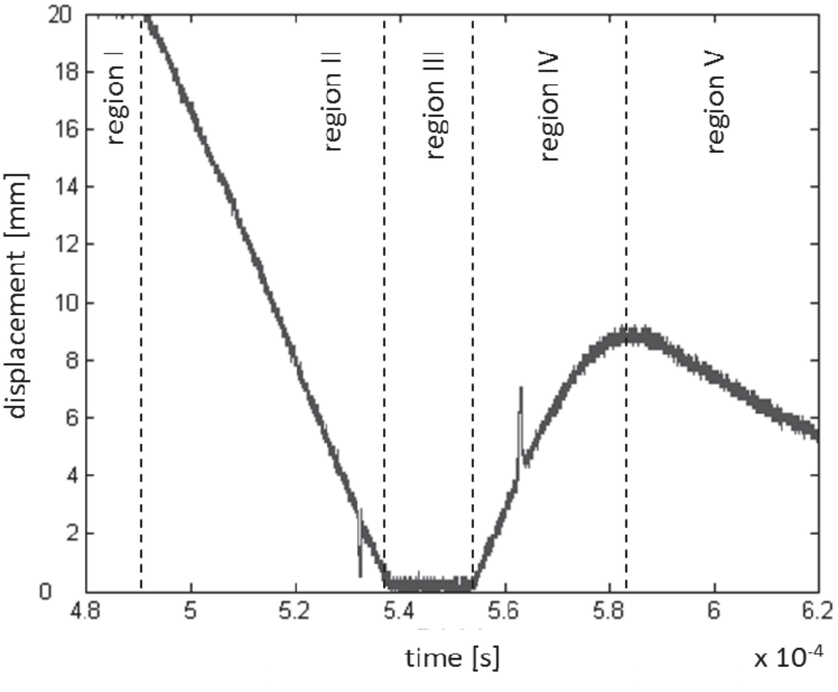

***Figure 10**: Time-displacement diagram of the forming tool*

Using an operating pressure of 150 bar as an example, Figure 10 shows the displacement of the punch during the forming of a sheet disc having a 15 mm wide web. The punch is in the stationary position (region I), forms the sheet (region II) up to rupture (region III) prior to springing back (region IV) and finally coming to rest (region V). It is agreeably noticeable that the punch does not require a longer acceleration phase to reach its final speed of 10.9 m/s and is not significantly decelerated during the forming process. The spring-back / post oscillations, which can be repeated several times according to the pressure, were a nuisance.

4 Summary

Numerous different equipment designs currently exist for determining material parameters in the high speed forming range. Only the mechanically and pneumatically operated testing devices currently offer the necessary flexibility for determining FLD's. However, these devices are frequently impaired by comparatively low forming speeds. Taking this into consideration, we produced our own equipment design that is characterised by particularly very stable forming conditions which are otherwise only obtained during quasi-static forming.

References

[1] *Wood, W.W.:* Experimental Mechanics at Velocity Extremes – Very High Strain Rates; Experimental Mechanics; 1967, S. 441-446.

[2] *El-Magd, E.:* Abouridouane, M.: Einfluss der Umformgeschwindigkeit und -temperatur auf das Umformvermögen metallischer Werkstoffe; Zeitschriftenartikel; Zeitschrift für Metallkunde 94. Jg., Nr. 6, 2003.

[3] *El-Magd, E.; Abouridouane, M.:* Characterization, modelling and simulation of deformation and fracture behaviour of the light-weight wrought alloys under high strain rate loading; Zeitschriftenartikel; International Journal of Impact Engineering Vol. 32, No. 5, 2006.

[4] *Siegert K.; Vulkan M.:* Superplastische Umformung von Aluminium-Blechen mit nachfolgendem hydromechanischem tiefziehen. In: 8. Sächsische Fachtagung Umformtechnik ISBN: 3-86012-158-8, S. 251-271, 2001.

[5] Seth, M.; Vohnout, V. J.; Daehn, G. S.; Formability of steel sheet in high velocity impact. Journal of Materials Processing Technology 168 (2005) 390–400

[6] Fr.-W. Bach, M. Rodman, A. Rossberg, J. Weber, L. Walden; Verhalten von Aluminiumwerkstoffen bei der elektromagnetischem Umformung. 2. KOLLOQUIUM ELEKTROMAGNETISCHE UMFORMUNG

[7] Yaldız, S.; Saglam, H.; Ünsacar, F.; Isık, H.; Design and applications of a pneumatic accelerator for high speed punching. Materials and Design 28 (2007) 889–896

[8] Kosing, O. E.; Skews; B. W.; A Investigation of high-speed forming of circular plates in a liquid shock tube. Int. J. Impact Engng Vol. 21, No. 9, pp. 801-816, 1998

[9] Kim, S.B.; Huh, H.; Bok, H.H.; Moon, M.B.: Forming limit diagram of auto-body steel sheets for high-speed sheet metal forming. Journal of Materials Processing Technology 211 (2010) 851–862

[10] M. Engelhardt, H. von Senden genannt Haverkamp, Y.Kiliclar, M. Schwarze, I. Vladimirov, D. Bormann, F.-W. Bach, S. Reese; Characterisation and Simulation of High-Speed deformation processes. 4th International Conference on High Speed Forming – 2010, Columbus

[11] A.A. Tamhane, M. Padmanabhan, G. Fenton, M. Altynova and G.S. Daehn; Opportunities in High-Velocity Forming of Sheet Metal. Metal Forming Magazine