Design and Analysis of a Deep Drawing and In-process Electromagnetic Sheet Metal Forming Process*

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Abstract

The design as well as the subsequent analysis of a deep drawing and in-process electromagnetic sheet metal forming calibration will be described in this paper. Due to the quite different forming processes concerning the occurred strain rates, an investigation on the microstructure of the formed workpieces will be pointed out. Furthermore, the design steps regarding the integrated tool coil will be presented and the resulting examples discussed. Finally, the setup of the integrated process as well as the feasibility will be shown on an exemplary semi-industrial workpiece.

Keywords

Electromagnetic sheet metal forming, Process integration, Microstructure

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[*] This work is based on the results of the Research Unit FOR443; the authors would like to thank the German Research Foundation for its financial support

1 Introduction & Motivation

The demands for lightweight construction become more and more important, for example in order to decrease fuel consumption in the transportation industry and thus the CO_2 emission as an environmental aspect. One possibility to realize such a concept is to optimize the design of the components on the one hand and, one the other hand, to apply "light" materials like aluminum.

Due to the smaller density and the comparably high strengths of aluminum alloys, for example the family of the 5xxx alloys are suitable for the use in lightweight car bodies instead of steel. The following diagram illustrates the increase of the weight proportion of aluminum within the European automotive branch over the last years [1].

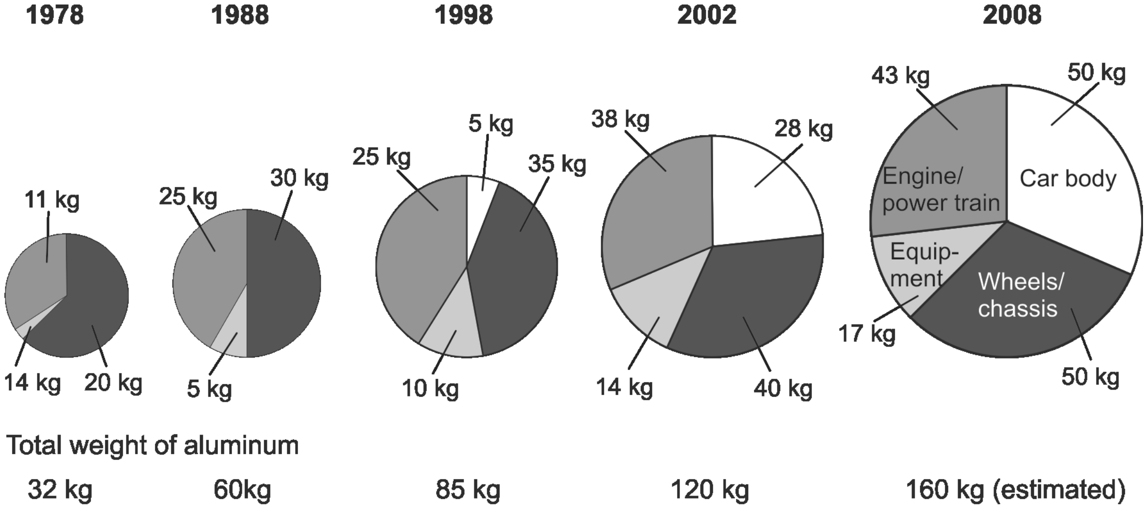


Figure 1: *Weight proportion of aluminum within the European automotive engineering [1]*

However, the formability of these materials is lower than that of common forming materials like carbon steels. Therefore, the realization of minor forming elements, as for example a door handle in an automotive door panel, can be quite difficult, so that a lot of drawing stages are necessary or even impossible with the conventional deep drawing process. Hence, the development of innovative technologies is indispensable.

An example of such an innovative technology is a combination of conventional deep drawing with electromagnetic sheet metal forming, where the electromagnetic calibration step is integrated in the deep drawing process. Due to this special combination the advantages of both processes can be merged.

In order to prove the potential of this combined process, investigations were performed on a semi-industrial demonstrator, which is based on the mentioned door handle.

2 Description of Deep Drawing and In-Process Electromagnetic Calibration

Deep drawing is one of the most important processes for forming sheets. Thereby, a wide range of different production sectors, like automotive parts, aircraft components, household articles or white goods, are covered. The deep drawing process is a process to manufacture a product, especially hollow bodies, from sheet metal. During the deep drawing process, an initially flat blank, which is clamped between the die and the blankholder, is usually pulled over the punch into the die to deform the clamped blank into the desired shape. Thereby, the blankholder prevents any wrinkling in the flange area and facilitates a controlled material flow into the die radius [2]. Due to the fact that extensive research work was done in the deep drawing technology over the last hundred years, a considerable amount of knowledge regarding the process parameters as well as their interactions could be established. Therefore, a lot of strategies to produce a desired geometry are known. However, the limits in the deep drawing process, especially when using materials with poor formability, are inter alia to be found in the realization of small minor forming elements as, for example, a door handle in an automative door panel. Here, the manufacturing is quite difficult, so a lot of drawing steps are necessary or even impossible with the conventional deep drawing process. The advantage of the electromagnetic sheet metal forming is the high potential for the calibration of such geometrical elements.

The process principle of electromagnetic sheet metal forming is described in detail in [3]. With regard to the in-process electromagnetic calibration, the tool coil has to be integrated in the deep drawing die, while the minor forming element is placed in the punch, as shown in Figure 2. According the process principle of the electromagnetic forming, the magnetic pressure which is needed to deform the workpiece acts only in the area, where the winding is located. Due to the defined position of the tool coil in the drawing die and geometrical element in the punch, special effort was put on the positioning to each other in order to achieve the desired geometry.

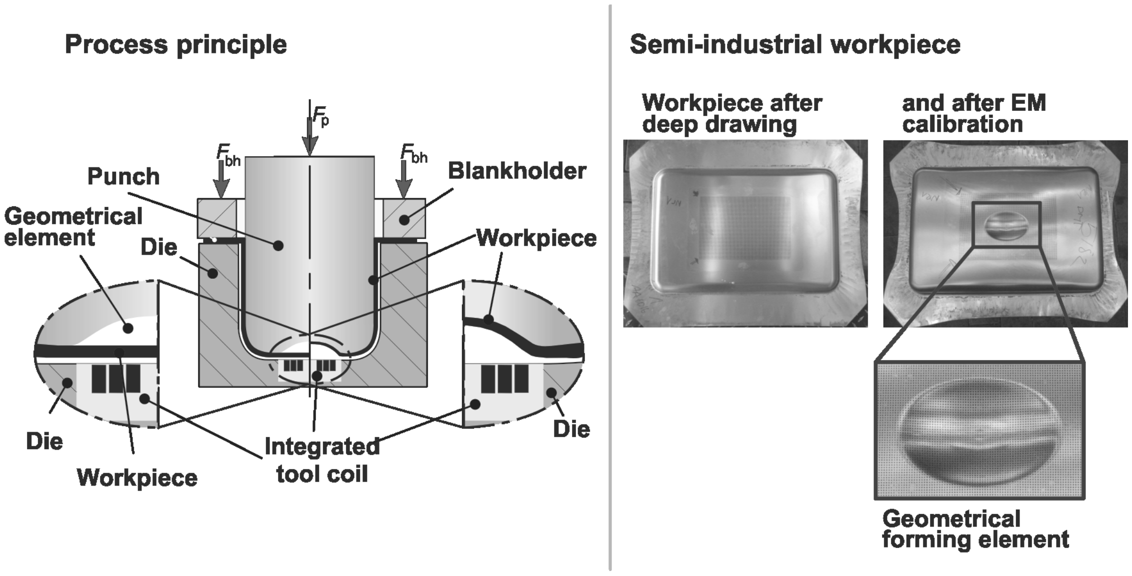


Figure 2: *a) Principle of the integrated process b) semi-industrial workpiece*

In order to design such a combination of deep drawing and in-process electromagnetic calibration and finally to show the feasibility as well as potential of this special combination, the following investigations are carried out. The analysis starts with the investigation of the microstructure of each single process and is followed by the design of the special tool coil geometry separately on the basis of the electromagnetic forming process alone.

3 Influence of the Strain Rate on the Material Microstructure

In order to identify the different forming mechanism of each single process within the process combination, a detailed analysis of the microstructure was carried out. Thereby, a light optical microscopy as well as a scanning electron microscopy (SEM) was performed in order to investigate the macrostructure of the samples and the grain boundary. Furthermore, a transmission electron microscopy allows the analysis of the dislocation structure. These different investigation options offer the possibility to establish an understanding of the forming mechanisms. All investigations are done on the aluminum alloy AA5182.

The investigated specimens were formed with different strain rates: quasistatic bulge tests and dynamic electromagnetic sheet metal forming, respectively. Thereby, a regular dot pattern was applied to the workpiece surface in order to characterize the strain distribution after the forming operation with the optical measurement system Argus developed by GOM [4]. So, it was possible to detect positions with equal strains in both workpieces. Furthermore, selecting the regarded specimen sections also the loading condition has to be also considered as the same. The photos taken with the light optical microscope are presented in Figure 3.

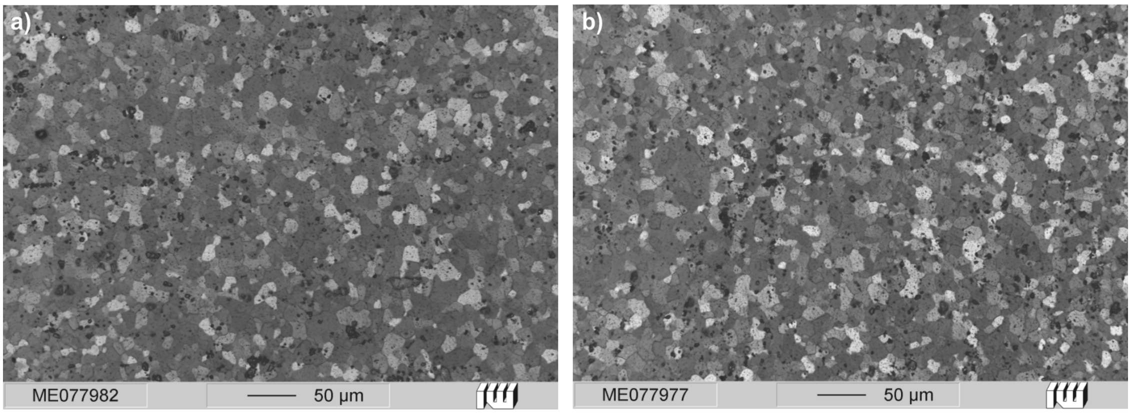


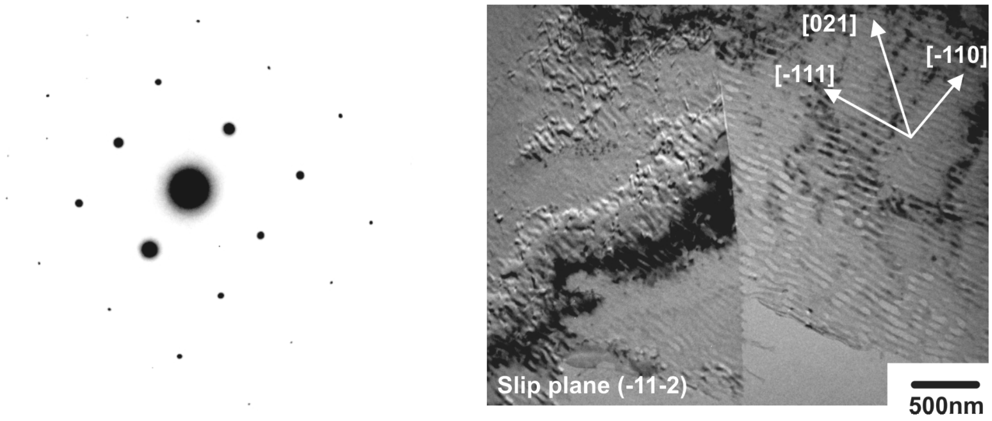
***Figure 3:** Microstructure of the a) quasistatically and b) dynamically formed workpieces made of AA5182*

The grain size of the formed workpieces is determined on the basis of DIN EN ISO 643. The grain size of the electromagnetically formed specimen is 9, while the grain size of the quasistatically formed workpiece could be determined as 8.5. Due to having the same strain on the analyzed specimen, only a small difference of the grain size was observed. Nevertheless, the grain size of the dynamically formed parts is smaller than the quasistatic ones (compare Figure 3a), indicating that the forming mechanism of both processes differ from each other.

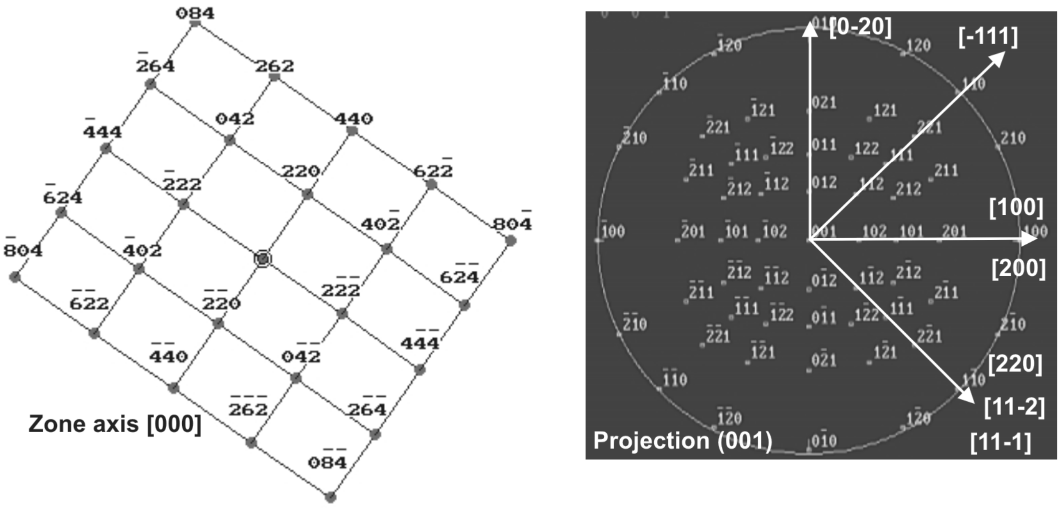
In order to obtain a deeper understanding of the dominating forming mechanism, an investigation on a microstructural level is necessary. Therefore, a transmission electron microscopy (TEM) was carried out. The specimens were prepared by means of wire-cut electrical discharge machining (EDM) in order to have the best sample quality and no influencing parameters (e.g. local heating) on the dislocation structure.

The aim of this analysis is the identification of microstructural phenomena, for example the preferred slip planes within the crystal, so that, on the one hand, the dislocation structure can be described depending on the forming parameters and on the other hand, the different forming mechanism can be explained.

On this basis a comparison on the microstructural level of different forming operations is also possible. As known from literature [5], the aluminum alloys have a face-centered cubic system and the preferred planes are (110), (100), (211), (111), (310), and (123). Due to the face-centered cubic system, parallel planes in the crystal, which interact with each other, can exist. Hence, the following approach, which can be described on the basis of Figure 4, was used for the analysis.


a) Diffraction pattern

c) Definition of the directions


b) Theoretical diffraction pattern

d) Stereographical projection

***Figure 4**: Approach to analyze the samples*

Due to the extremely small specimen size of one or two grains, a transmission electron microscope was applied for the analysis. Thereby, the reflected electrons are projected on a detector screen, and the diffraction pattern of the crystal (see Figure 4a), indicating the crystallographic orientations of the investigated samples, is received. Then, the Miler indices of the crystal, which indicate the directions, can be defined. Knowing the distance and the angle of different planes obtained by the diffraction pattern and their mathematic correlations, the theoretical diffraction pattern can be determined (compare Figure 4b). Now, the achieved directions are transferred to the observed grain (see Figure 4c), and a stereographical projection is performed. This stereographical projection allows a well arranged two-dimensional description of directions and orientation of planes. This orientation is presented through the surface normal. Due to this, it is possible to detect parallel planes within the crystal. The orientations of the analyzed crystal in the standard (001) stereographical projection are presented in Figure 4d. Thus, the parallel planes within the crystal as well as the correlations between the planes could be identified.

The results obtained by using the described approach are shown in Figure 5. In Figure 5a the microstructure of the quasistatically formed workpiece is presented, while the electromagnetically formed sample is given in Figure 5b. In this investigation, the preferred direction of the sample taken from the quasistatic formed workpiece is the [100] direction. This means that the texture is oriented also in [100] direction. Contrarily, the electromagnetically formed specimen has three preferred directions [111], [110] and [100], which could be observed during the analysis. This means, that more dislocation motion occurs on the one hand and, on the other hand, a marginal texture could be detected.

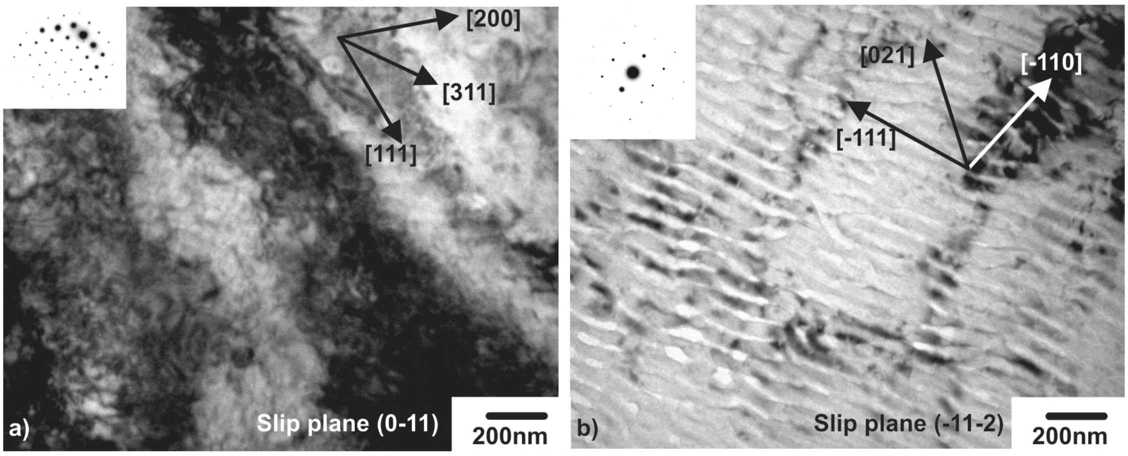


***Figure 5**: a) quasistatically formed sample b) electromagnetically formed sample*

In Figure 5b, some wavelike lines with a width of about 10 up to 40 nm can be perceived, while this wavelike structure in Figure 5a has a width of much more than 40 nm. Furthermore, this phenomenon is rare in the microstructure of the quasistatically formed workpiece, whereas approximately 30% of the grains belonging to the electromagnetically formed sample show this wavy formation. This wavelike structure is the result of the evolution of the gliding planes due to the dislocation motion. Investigations concerning the localization of plastic strain as well as the formation of waves of plastic flow are described in [6, 7]

Seen from the microstrctrural point of view, the following forming mechanisms can be distinguished according to [8]

- Change in the resistance to motion of dislocation
- Increase of temperature
- Concentration of dislocations

But in case of parallel planes occurring by the electromagnetically formed workpiece, only one of these forming mechanisms is responsible for the deformation.

However, in case of the electromagnetically formed samples, parallel planes could be detected by means of the described stereographical projection. Consequently, more dislocations could slide. All mentioned aspects enhance the quality of the forming process so that the formability of the material could be increased.

4 Pre-Experiments to Design the Integrated Tool Coil

Preparing the combined process, pre-investigations regarding the electromagnetic forming step separately and using a plane tool coil were carried out. The major function of the coil winding is to apply an appropriate pressure pulse as well as pressure distribution onto the surface of the workpiece [3, 11, 12]. In this context, the influences of different pressure distributions resulting from different coil geometries on the quality of the forming results were analyzed at the Technical University of Dortmund. All tool coil and winding geometries had been designed and realized at Poynting GmbH. In this close collaboration several loops have been performed.The forming task here is an elliptical geometry, which is comparable to a door handle (shown in Figure 2). The investigation starts with a tool coil with an elliptical winding of eight turns. The outer dimensions correspond to the forming task, as shown in Figure 7a. Thereby, the turns of the winding have a constant cross section and the distance between two adjacent turns is equal. All experiments are done with the aluminum alloy AA5182 with a sheet thickness of 1.2 mm. The resulting workpiece geometries achieved by different charging energies are measured with an optical three-dimensional digitizer (ATOS I by GOM) and compared with the desired shape. The occurring deviations are presented in Figure 6.

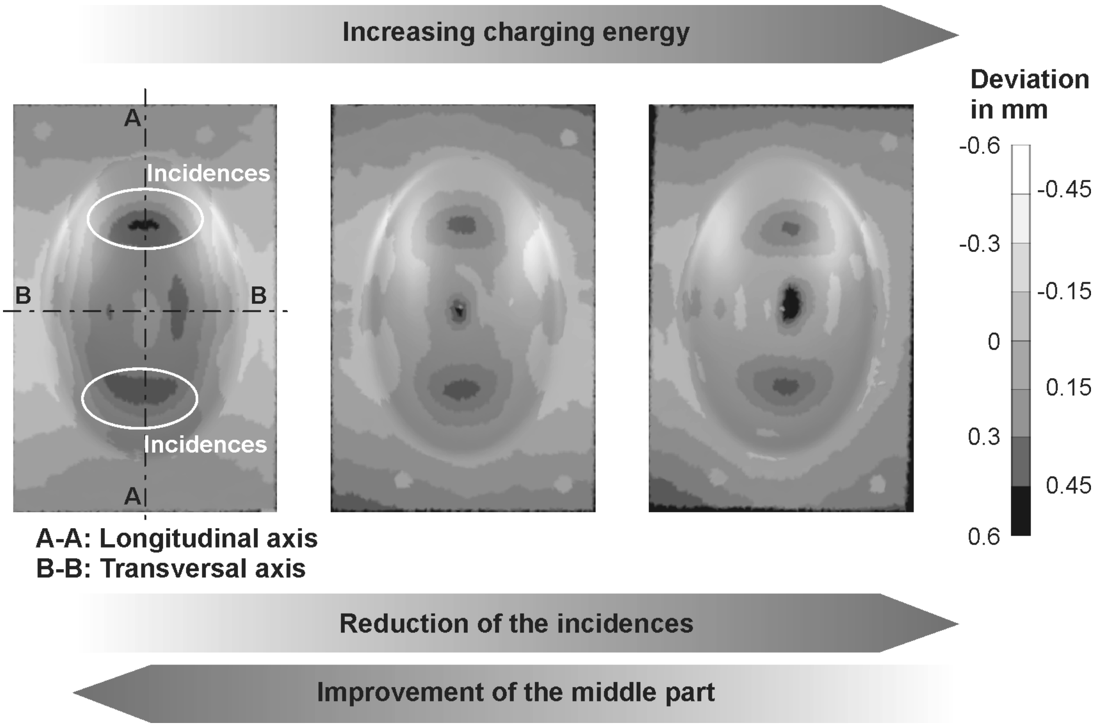
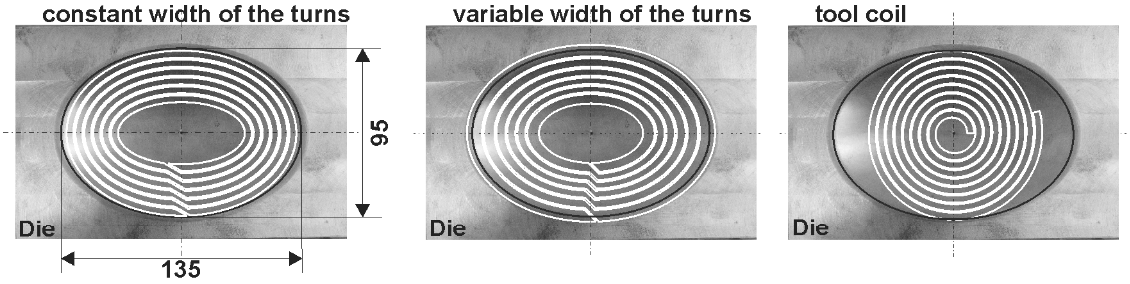


***Figure 6**: Contour courses of workpieces achieved with different charging energies*

A comparison of these geometries shows that by adapting the charging energy, either the middle of the workpiece can be reached in a good order or the incidences on the longitudinal axis (marked in Figure 6) are minimized, but no overall satisfying result is achievable.

In order to optimize the forming result, the pressure distribution has to be adapted. Therefore, a tool coil, which consists of eight turns with variable cross section as well as variable distance between the turns, was built and analyzed. This strategy, namely changing the turn density of the tool coil, was successfully applied in [12]. Both tool coils are presented in Figure 7a+b.

Position of the winding to the die



a) Elliptical tool coil with constant width of the turns

b) Elliptical tool coil with variable width of the turns

c) Rotationally symmetric tool coil

Data of the different tool coils

	a)	b)	c)
Number of turns	6	6	8
Height of the turns	14	16	7
Width of the winding	30 mm transversal 30 mm longitudinal	33.5 mm transversal 40.9 mm longitudinal	38 mm
Length of the longitudinal axis	130 mm	140 mm	98 mm
Length of the transversal axis	95 mm	190 mm	98 mm
Manufacturing of the winding	Water jet cut	Water jet cut	Manual wound

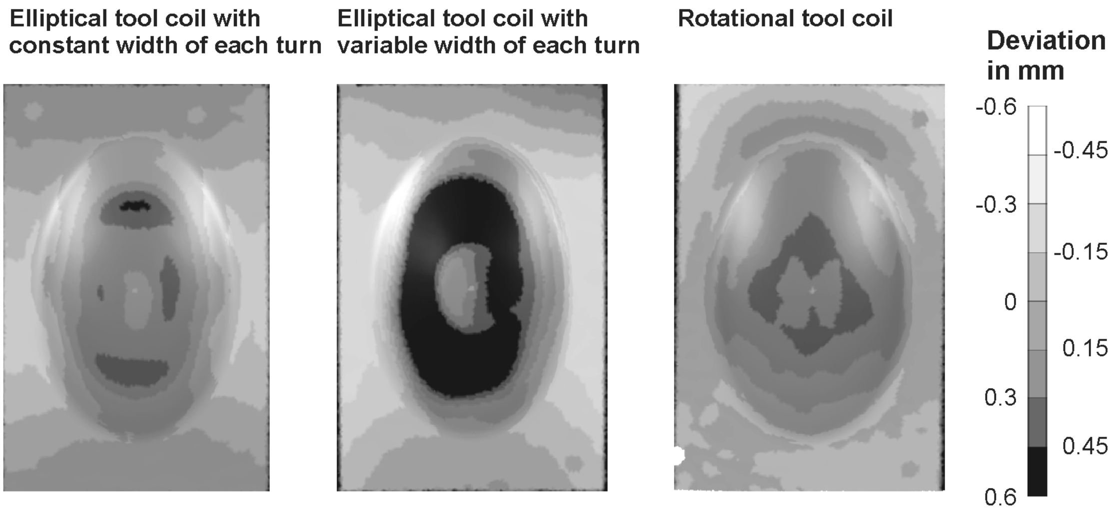
***Figure 7**: Description of the different tool coils*

Unfortunately, the desired geometry optimization regarding the elliptical geometry could not be achieved with this material (compare Figure 8). In general, the same effects occur using the tool coil with constant width of turns. Providing approximately the same geometric quality in the middle of the part, the occurring incidences are even stronger in case of the tool coil with variable width of turns.

The next iteration, the pressure distribution is optimized on the basis of the forming result of the previously described tool coils. Due to the incidences on the longitudinal axis, the pressure has to be increased to complete the form filling. One possibility to do so is to move the pressure maximum, which is usually located in the middle of the coil winding. Consequently, the length of the longitudinal axis of the tool coil has to be reduced. To ensure a pressure near the die's edge, the width of the winding has to be increased simultaneously. Taking these actions results in a nearly rotational symmetric tool coil (compare Figure 7c). One advantage of this tool coil geometry regarding manufacturing aspects is the easy producibility in contrast to the elliptical tool coils. The forming results of this tool coil geometry are included in Figure 8, too.

In contrast to the elliptical tool coils, the rotationally symmetric one shows significantly lower deviations. The form filling is more homogenous and no incidence could be detected by an optical evaluation. Comparing all pictures, it can be seen that the best results could be achieved with the rotationally wound tool coil. Therefore, this coil geometry was chosen for the investigation of the combined deep drawing and electromagnetic sheet metal forming process.

a) Areal deviation



b) Contour course

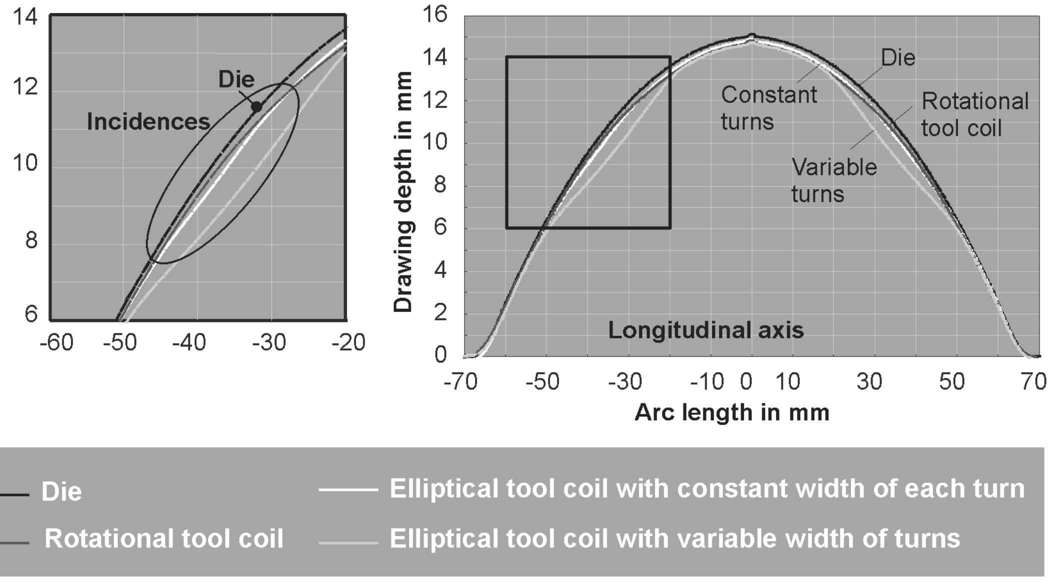


Figure 8: a) Areal deviation b) Contour course

5 Discussion of the Results of the Deep Drawing and In-Process Electromagnetic Calibration Process

Apart from the feasibility of the electromagnetic calibration itself, there are additional restrictions regarding the deep drawing process. One impotant aspect is the remaining formability for the electromagnetic calibration operation, which will be reduced by all previous forming operations due to strain hardening and thinning effects.

However, in contrast to the plane tool coil, which was used in the pre-investigations, at Poynting GmbH a die with integrated tool coil has been adapted to the three-dimensional surface of the punch (resp. the workpiece).Therefore, the integrated tool coil has to be slightly curved, compare Figure 9. Furthermore, special measures have to be taken on the drawing die, especially on the embedding, as well as on the including winding: high voltage insulation between the single turns as well as between the winding and the workpiece; high strength to resist the deep drawing forces and to resist the impulse load of the winding during electromagnetic calibration; high wear resistance of the surface and adaptability to the forming press.

These demands require special and different materials in order to fulfill the described tasks. For the purpose of stability and adaptability to the forming press, a hardwood plate is used as a fixture, to which the curved tool coil is mounted. The slightly curved surface of the deep drawing die was realized by means of casting polyurethane (PU) to ensure the wear resistance during deep drawing. Within the prototypical testing of about 50 experiments, there is no significant abrasion of the polyurethane die.

The special deep drawing die including the tool coil as well as the necessarily modified EMF equipment was designed and manufactured at Poynting GmbH. The realized experimental setup is presented in Figure 9.

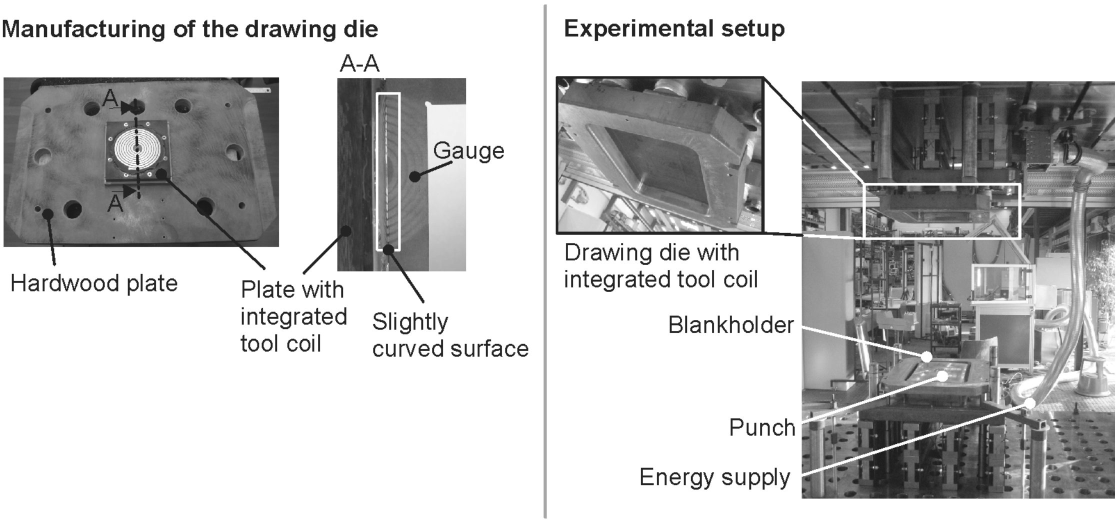
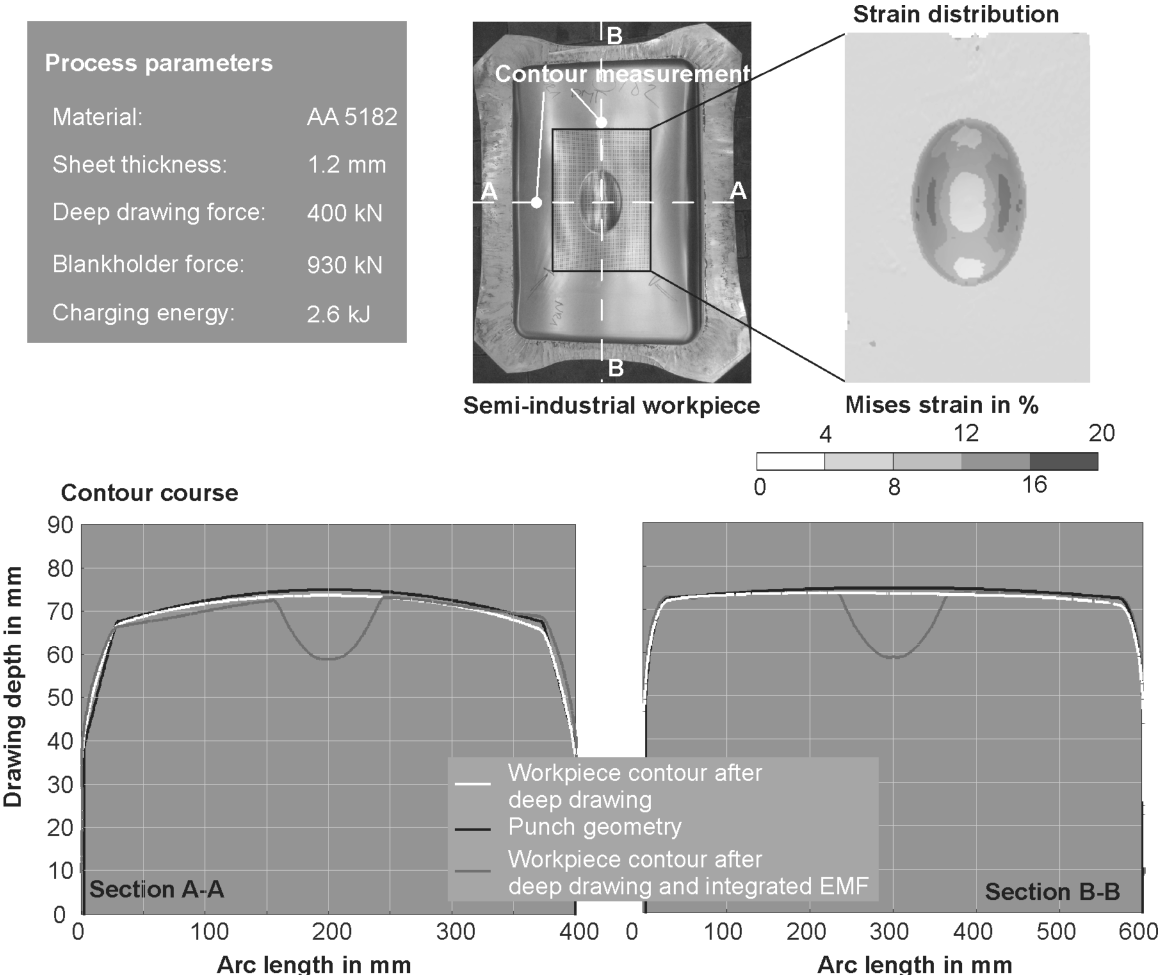


***Figure 9**: Experimental setup*

Representative results of the deep drawing and in-process electromagnetic forming operation using the described equipment is presented in Figure 10. Applying a charging energy of 2.6 kJ, the geometrical forming element could be realized without cracking.

The resulting strain distribution of the workpiece was determined by using the optical measurement system Argus developed by GOM. Using this evaluation tool, the maximum

Mises strain of the formed workpiece is approximately 17%. As known from literature the strain at failure by quasistatic loading of the aluminum alloy AA5182 is higher, namely in the range of 23-30% [9, 10], and additionally, the strain at failure increases with higher strain rates [11]. This means, that the formability of the used material is not exhausted and the described process strategy is arranged in a reliable process window. Furthermore, the geometry of the whole part could be achieved with good accuracy and without any significant deviation from the desired shape, as shown by the contour courses of the longitudinal as well as transversal axis. Moreover, no visible incidences could be detected comparable to the pre-investigation with the plane rotational symmetric tool coil.



Process parameters

Material:	AA 5182
Sheet thickness:	1.2 mm
Deep drawing force:	400 kN
Blankholder force:	930 kN
Charging energy:	2.6 kJ

__Figure 10__: Results of the combined process

All investigations were also carried out with the aluminum alloy A6016 and the results show qualitatively comparable results.

6 Conclusion & Outlook

In order to analyze the integrated process of deep drawing and in-process electromagnetic forming, both processes were investigated separately on a microstructural level. Thereby, the differences caused by the varying strain rates are described. Further investigation of the microstructure could consider the determination of the temperature by means of an EDX-Analysis in TEM which are attained during the forming process. Moreover, the microstructural development in the combined process will be analyzed.

Regarding the integrated process, different tool coils were designed and tested on plane workpieces in order to achieve a homogenous form filling. Here, a rotationally symmetric tool coil showed the best results, although the desired die shape describes nearly an ellipse. These investigations will be extended to other complex geometries and other materials.

Finally, the feasibility of the described process combination of deep drawing and in-process electromagnetic calibration could be successfully proved. The analysis shows that the remaining formability was sufficient for the following calibration process and the achieved strain was lower than maximum strain of failure in quasistatic loading. So, the potential regarding forming more complex geometries is available and will be analyzed in detail in future work.

References

[1] *Jopp, K.:* Aluminiummotor in einem Guss. VDI nachrichten, 08/2003

[2] *Lange, K.:* Umformtechnik, Blechbearbeitung, Band 3, ISBN 3540500391

[3] *Beerwald, C.:* Grundlagen der Prozessauslegung und –gestaltung bei der elektromagnetischen Umformung (in German), Ph.D.-Thesis, Dortmund, Germany, 2004, ISBN 3-8322-4821-2

[4] www.gom.com

[5] *Hirsch P. B., Howie A., Nicholson R. B. at all:* Electron microscopy of thin crystals, London, Butterworths, p.503, 1965

[6] *Zuev, L.:* On the waves of plastic flow localization in pure metals and alloys, Ann. Phys. (Leipzig) 16, 4, p.p.286 – 310, 2007

[7] *Panin V. E., Grinyaev V. L, Danilov V. L. at all:* Mehrskalige Strukturstadien bei plastischer Umformung und Bruch, Novosibirsk, Wissenschaft. Sibir. Niederlassung, S. 255, 1990

[8] *Starenchenko, V. A.; Solov'eva, Y. V.; Abzaev, Y. A.; Kozlov, E. V.; Shpe°zman, V.; Nikolaev, V. I.; Smirnov, B.I.:* Evolution of dislocation structures having various orientations in strained single crystals of the alloy Ni3Ge. Physics of the Solid State, USA * vol 40 (April 1998), no 4, p 618-25, 19 refs. Translation of: Fizika Tverdogo Tela, Russia, vol 40 (April 1998), no 4, p 672-80

[9] *Ayres, R. A.; Wenner, M. L.:* Strain and strain-rate hardening effects on punch stretching of 5182-O aluminium at elevated temperatures. Metallurgical Transaction A, Vol. 10A, pp. 41-46, 1979

[10] *Takata, K.; Ohwe, T.; Saga, M.; Kikuchi, M.:* Formability of Al-Mg-Alloy at Warm Temperature. Materials Science Forum, Vols. 331-337, pp. 631-636, 2000

[11] *Vohnout, V. J.:* A Hybrid Quasi-Static-Dynamic Process for Forming Large Sheet Metal Parts from Aluminum Alloys, Ph.D.-Thesis, Ohio State University, Ohio, USA.

[12] *Psyk, V.; Beerwald, C.; Henselek, A.; Homberg, W.; Brosius, A.; Kleiner, M.:* Integration of Electromagnetic Calibration into a Deep Drawing Process of an Industrial Demonstrator Part, Key Engineering Materials Vol. 344 (2007) pp. 435-442, 2007, Trans Tech Publications, Switzerland