Aspects of Die Design for the Electromagnetic Sheet Metal Forming Process[*]

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Abstract

Within the electromagnetic sheet metal forming process, workpiece velocities of more than 300m/s can occur, causing typical effects when forming into a die, which will be described and discussed in the present paper. These effects make numerous demands regarding the die design. In order to analyze these requirements, experimental as well as numerical investigations have been carried out. Thereby, special focus is put on the possibilities to accomplish these requirements, which are discussed in the following.

Keywords:

Electromagnetic sheet metal forming, Tool design, Physical Vapor Deposition (PVD)

1 Introduction

The electromagnetic forming process (EMF) is a highly dynamic process using pulsed magnetic fields to form metals with high electrical conductivity such as aluminum. The process principle as well as the forming behavior of the workpiece is described in detail in [1]. When forming into a cavity, there are several requirements concerning the design of the dies. On the one hand, the feasibility of different geometrical forming elements is essential and on the other hand, the lifetime of the stressed parts of the die as well as the resulting workpiece quality is important.

Due to the process principle local workpiece velocities of more than 300 m/s are achievable within the EMF process, whereby a high contact force between the workpiece

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and the die occurs during the impact (compare Figure 1). This causes typical effects when forming into a die:

- Rebound effect (described in [1]) due to high kinetic energy
- Wear, friction as well as fretting due to high normal contact forces combined with tangential movement of the workpiece

The kinetic energy of the workpiece, which strongly depends on the velocity as well as its distribution, is an important aspect regarding the die design for the EM sheet metal forming process. The velocity and its distribution can be strongly influenced by pressure distribution, the pressure over time curve, and the die design, e.g. by using geometrical inserts. The first mentioned parameters have already been analyzed in [1, 2], whereas the present investigations concentrate among other thing on the variation of the geometrical inserts in order to identify geometrical influencing parameters on the rebound effect.

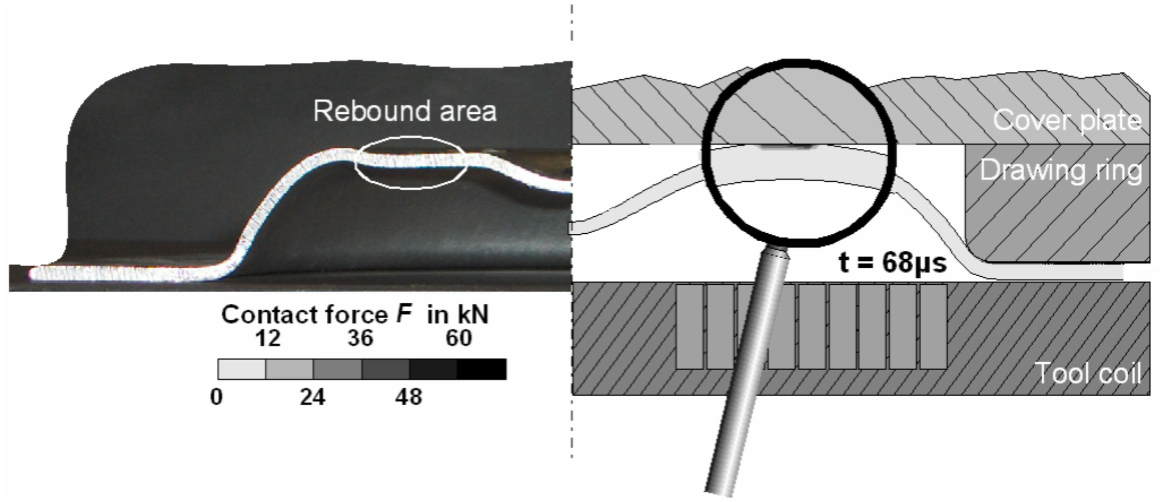


***Figure 1**: Rebound area and contact zone*

The strongest loads have been detected in the zone of the first impact between workpiece and die, compare Figure 1. Here, an intermediate forming state in the place where the first contact on the cover plate occurs is highlighted in **Figure 1**. This contact zone is exposed to high stresses resulting from extensive surface wear and friction caused by high normal contact forces combined with tangential movement of the workpiece. At present, lubricants are used to reduce these undesired effects but an accumulation of the lubricants causes geometrical deviations of the workpiece. In order to reduce these effects, especially the occurring surface defects caused by fretting, the most stressed part of the die, namely the cover plate, will be deposited with different thin Physical Vapor Deposition (PVD) layers.

PVD is a well-established technology used to enhance the properties of tools and precision components as well as to improve their behavior and performance. Within the process the coating material is transferred from solid to vapour phase by means of different energy sources [4]. The advantages of this technology are already utilized to extend the lifetime of forming and machining tools and, therefore, to reduce costs. For this purpose, various kinds of thin layers with different morphologies have been deposited on forming tools to reduce friction and wear. In this way fretting on tools can be prevented. The selection of the individual hard layer system strongly depends on the material to be processed and the forming conditions such as temperature, pressure, forming velocity, etc. [5]. The most common wear protection layers applied on forming tools and plates are TiC-, TiCN-, TiN-, TiAlN, and CrC-layers [6]. In addition, carbon layers like DLC (diamond like carbon) with a high wear and corrosion resistance [8] as well as solid lubricant coatings with a low friction coefficient have proved to be particularly favorable systems [9].

Both die concepts concerning the geometrical inserts as well as the coating strategy, will be described and discussed in the following chapters. Initially, the influence of the geometrical stiffness on the forming process will be investigated. In order to enhance the resistance of the cover plate against wear and impact, an innovative concept concerning the tool surface modification has been developed within the scope of this research work and will be described in the following.

2 Description and discussion of the experiments

2.1 Experimental setups

The experimental setup for the analysis regarding the geometrical inserts (case A), shown in **Figure 2**, consists of a spirally wound tool coil, a sheet workpiece, a drawing ring, a cover plate as well as different forming elements which can be adapted to the cover plate. Due to the modular die system an easy change of the forming elements is possible. A vacuum port is attached to the cover plate as well as to the inserts to ensure a vacuum inside the die and to avoid pressurized air which acts against the magnetic pressure. The used workpiece material was aluminum (Al 99.5) with a thickness of 1.5 mm, which was formed with a charging energy of 1,260 J.

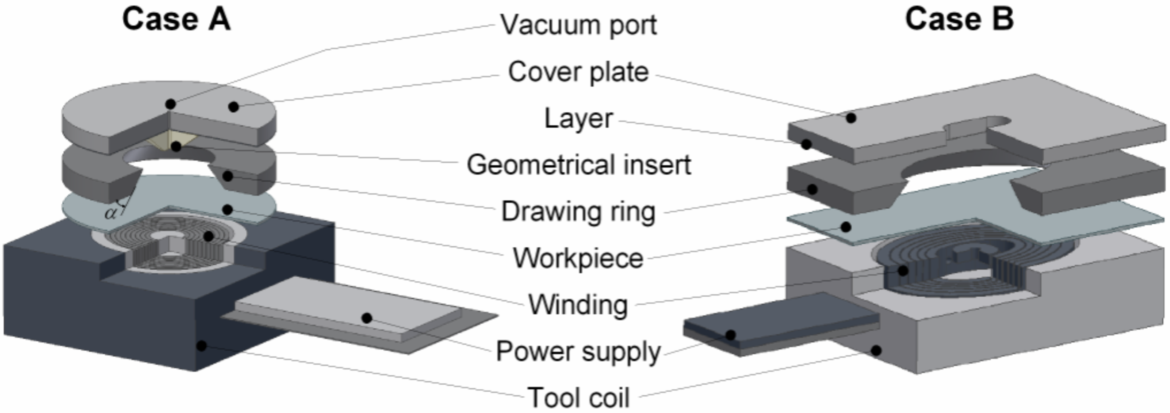


***Figure 2**: Experimental setups*

With the purpose to investigate the behavior of different coatings in high dynamic processes (case B), an oval tool coil was used. The change towards the oval coil was done because a larger area of the coated cover plate is stressed which simplifies the analysis. To characterize the behavior of the layers during a small batch production, the experiments are repeated 40 times. The charging energy was kept constant at 2,560 J throughout the entire sequence of experiments. The used workpiece material was aluminum (Al 99.5) with a thickness of 2.0 mm. The setup, consisting of an oval tool coil, a workpiece, an oval drawing ring as well as a coated cover plate, is shown in **Figure 2**. Due to the hole in the center of the cover plate no evacuation is necessary. All experiments are done with a Maxwell pulse generator with following properties: Inductance L of 44 nH, capacity C of 960 µF and, an eigenfrequency f of 23 kHz.

In order to enhance the wear resistance of the cover plate against the impact and to reduce the friction between the aluminum workpiece and the cover plate, three different types of layer systems have been deposited. In this context, hard layers (DLC with and without H-doping), soft layers (MoS_2) and multilayer systems (Ti / TiAlN, TiAl / TiAlN) containing six individual layers have been deposited. To improve the adhesion between the surface layer and the substrate Cr-adhesion layers have been applied [13, 14]. The deposition has been carried out in PVD-Device (CemeCon, Deutschland), using the MF magnetron sputtering with a balanced magnetic field. The coating parameter values are summarized in Table 1.

Parameter	Values
Electric power	9.5 kW (Ti-, TiAl-cathodes) 2.5 kW (Cr-cathodes) 2 kW (MoS_2-cathodes)
MF-voltage / Frequency	25 V / 350 kHz
Plasma gas	argon, krypton
Reactive gas	nitrogen (CrN), acetylene (H-doped DLC)
Dimension of the cathodes	Ti (500 x 88 mm) TiAl (500 x 88 mm) Cr (500 x 88 mm) MoS_2 (200 x 88 mm) C (500 x 88 mm)

***Table 1**: Coating parameters*

The layer systems have been deposited on three different samples geometries: rectangular specimens (29 x 19 x 12 mm in size), cylindrical specimens (with a diameter of 40 mm, and a thickness of 12 mm) and the cover plates (200 x 140 x 12 mm in size), while tempered steel (1.2067) has been employed as substrate material. The rectangular specimens have been used to test the layers concerning their adhesion, their thickness, and hardness, while the cylindrical ones have been utilized to measure the sliding wear resistance. In order to characterize the layer systems during and after electromagnetic forming coated cover plates have been employed. The layer thickness has been determined by means of calowear tests with a 100Cr6 ball (20 mm diameter). The layer adhesion has been analyzed by means of scratch tests with a maximum load of 200 N, while the critical load has been determined by light optical microscope and acoustic emission. A pin-on-disc tribometer has been employed to test the friction and sliding wear characteristics of the layer systems in dry media. The tests have been performed using a 100Cr6 ball with 6 mm diameter and a load of 5 N. Three wear tracks with a diameter of 10 mm, 14 mm, and 18 mm and a constant track speed of 0.4 m/s have been adjusted. During the test the samples have been continuously monitored with regard to their wear behavior. The material loss is determined by weighing and/or measuring the profile of the resulting wear track. The layer hardness has been acquired by microhardness tests using a precision diamond indenter with a load of 50 N.

Scanning Electron Microscopy (SEM) and Light Microscopy (LM) have been employed to investigate the relationship between the different kinds of layers and the appropriate tribological properties of the coated cover plates after electromagnetic forming application. In addition, the surface topology was optically scrutinized with a confocal microscope.

2.2 Influence of the geometrical stiffness on the forming process

In [1], the so-called rebound effect was indicated as a negative influence on the workpiece geometry when forming into a cylindrical cup (see Figure 1). In order to identify geometrical influencing parameters on this rebound effect, an investigation concerning the die design has been carried out. The material, the sheet thickness, the depth as well as the tool coil geometry were chosen to be constant.

The die has been modified regarding the applied ring-shaped pressure distribution: the used cavity consists of flat bottoms and conical elements. In order to be able to vary the local stiffness of the workpiece, geometrical inserts which have been adapted to the cover plate are used. The results of this investigation will be explained exemplarily on the basis of selected geometrical elements, shown in **Figure 3**.

Process parameters

Material:	Al 99.5	Forming machine:	Maxwell; L = 44 nH, c = 960 µF, f = 23 kHz
Sheet thickness:	1.5 mm		
Angle α_I:	45°	Charging energy:	1,280 J
Angle α_{II}:	26.6°		

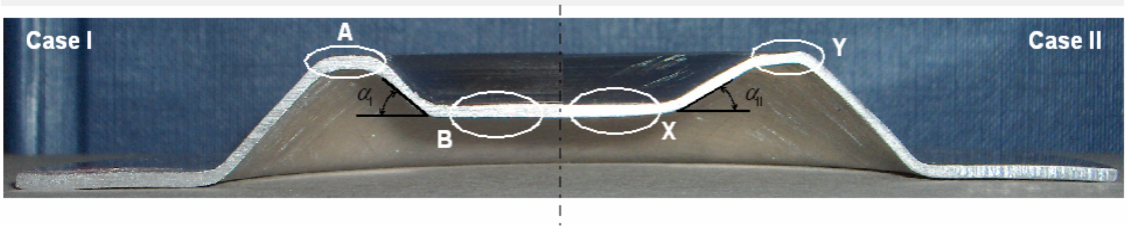


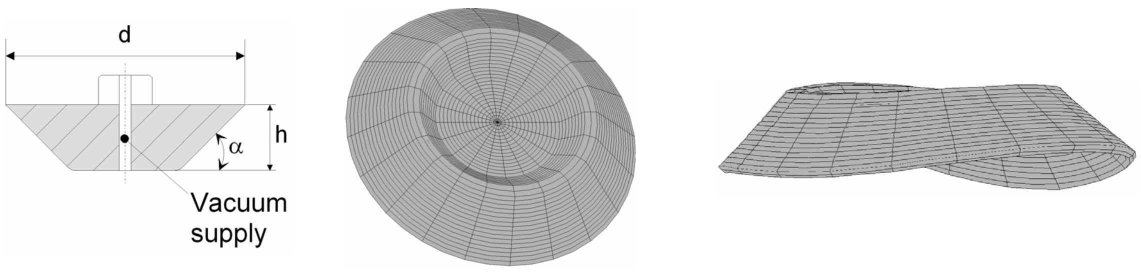
Figure 3: *Exemplary results by using different geometrical inserts as forming elements*

In order to keep as many parameters as possible constant, only the angle α has been varied (compare Figure 3). The photo shows that, in general, a good form filling is achieved in both cases. Here, it is remarkable that the flat areas marked as B in case I and X in case II are achieved in good order. The main difference of the two realized workpiece geometries is the geometrical stiffness, although the added geometrical inserts look quite similar. Regarding the achieved form filling in case II, a geometrical deviation can be observed in the ring-shaped area Y. The comparison with case I shows that by increasing the geometrical stiffness of the workpiece this effect on the workpiece could be significantly reduced. The desired contour could be achieved and no measurable geometrical deflection was detected, compare Figure 3.

In order to compare different geometries in a simple way, the significant value *K* is introduced to define the geometrical stiffness of the desired workpiece geometry. The geometrical stiffness K of the workpiece can be roughly estimated with the knowledge of the first eigenfrequency via the following formula [10].

$$K = (2\pi * f)^2 * m \tag{1}$$

Thereby, the eigenfrequency f as well as the mass of the workpiece m were calculated with a modal analysis in MSC.Mentat. The used method to determine the eigenfrequencies was Lanczos. In doing so, the ideal geometry concerning the design drawings is assumed and the undeformed flange area is neglected in the modeling of the workpiece because the flange increases the stiffness of the different geometries in the same manner. Furthermore, rigid body movements of the workpiece are allowed. This means that the first six eigenfrequencies are zero so that the seventh one, which is the real first eigenfrequency, is used. The calculated results for this eigenfrequency as well as the appropriate mode shape are summarized in Figure 4. A comparison of the different inserts has shown that the first eigenfrequency characterizes the bending mode shape in all regarded cases, whereas the corresponding eigenfrequency is quite different.


Geometrical insert **Undeformed shape** **Bending mode shape**

	Case I	Case II	Case III
Geometrical properties	d = 40 mm h = 5 mm α = 45°	d = 40 mm h = 5 mm α = 26.6°	d = 40 mm h = 11 mm α = 45°
Estimated values	f = 2589 Hz $m = 0.156*10^{-1}$kg **K = 4,128,083 N/m**	f = 2448 Hz $m = 0.156*10^{-1}$kg **K = 3,690,686 N/m**	f = 2807 Hz $m = 0.156*10^{-1}$kg **K = 4,852,540 N/m**

Figure 4: *Results determined by a modal analysis in MSC.Mentat*

The results of this analysis substantiate that by increasing the geometrical stiffness the rebound effect and the geometrical deviations respectively, as shown in **Figure 3**, could be reduced.

The long-term goal of this proposed design method using a modal analysis is to evaluate the feasibility of geometrical elements by means of electromagnetic forming. On this basis, a catalogue will be established listing different geometrical elements that could be assembled in order to estimate the total stiffness of the desired geometry. Thus, the feasibility of complex shapes can be appraised. Here, it is important to find balance between the required geometrical stiffness to realize a component and the maximum formability of the used material (e.g. thinning), which is acceptable regarding technical as well as functional requirements. This requires the improvement of the proposed method to realize the described approach.

Further effects concerning the die and the workpiece quality as well have been observed during these experiments. On the one hand, surface defects at the workpiece have been detected due to the accumulated lubricant and, on the other hand, fretting occurs between the aluminum sheet and the die made of tempered steel (1.2067). In order to improve the workpiece surface and to avoid the occurred fretting, the die, especially the cover plate in the present investigation, should be coated with different methods. The approach and the results of this strategy are described and discussed in the following.

2.3 Characterization of the different layers

In order to develop an appropriate layer system for the electromagnetic forming processes with high wear and impact resistance, the layer systems have firstly been empirically investigated (Table 2). Based on the attained results a selection of layer systems has been conducted.

	Ti/TiAlN-multilayer	TiAl/TiAlN-multilayer	DLC	DLC (H-doped)	MoS_2
Critical load [N]	125	73	72	108	80
Microhardness [HV]	638	935	1506	2338	979
Thickness [µm]	7,55	4,8	4,8	6,36	3,59
Wear coefficient	18,5 x 10^{-3}	9,54 x 10^{-3}	4 x 10^{-4}	2,1 x 10^{-4}	No weight loss determined

***Table 2**: Results of the layer characterization*

The results of the scratch test show a variation of the critical scratch load between 72 and 125 N, which demonstrate a high adhesion for all layer systems. All deposited layer systems exhibited thicknesses between 4 and 7 µm. In **Figure 5** it can be seen that the metallic layer is three times thicker than the TiAlN nitride layers in the Ti/TiAlN layer systems. In the TiAl/TiAlN multilayers the ratio between TiAl metallic layer thicknesses and TiAlN layers is about 2. This causes, on the one hand, a higher ductility of the layers and, on the other hand, this is associated with a low hardness as well as a low wear resistance (Table 2). Therefore, further layer and process optimization is needed as well to improve the properties of these layer systems and to adapt them to the demands of the electromagnetic sheet metal forming process.

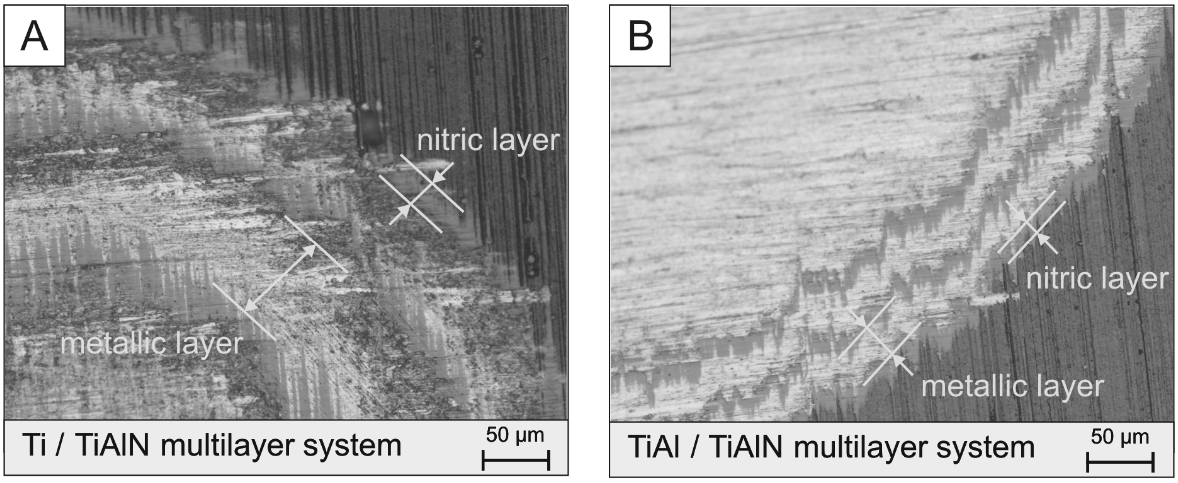


***Figure 5:** Light microscopy analysis of multilayers after calowear test*

The wear coefficients increase from Ti/TiAlN layer system to H-doped DLC layer system, which correspond to the hardness of the layers. An exception has been shown in case of MoS_2-layers, although their low hardness exhibits a high wear resistance. This is caused by the solid lubricant effect of MoS_2 layer [12]. The measurements of the wear resistance show neither a weight loss of the layer nor a significant layer abrasion, even at a wear distance of 4,500 m. Based on the layer system's properties it can be established that H-doped DLC and MoS_2 layer systems, too, show the best performance. Therefore, they can be evaluated as appropriate layer systems for the EMF process.

2.4 Comparison and discussion of the coatings

Cover plates coated with H-doped DLC and MoS_2 layer systems have been investigated during electromagnetic forming of aluminum sheets and after 40 impacts. The results have been compared with uncoated cover plates, whereas the sheet has been lubricated before each forming process. Furthermore, special emphasis was put on the aluminum sheet quality throughout the investigation.

After the electromagnetic forming process a characteristic oval surface groove has been observed on the surface of all cover plates. This groove consists of two tracks: one on the long axis side and one track on the short axis side (see Figure 6). To evaluate the relationship between layer systems and tribological properties of the coated cover plates after electromagnetic forming, the cover plates and the formed Al-sheets have been examined in the Scanning Electron Microscopy (compare Figure 6C - G). Additionally, the surface topology has been scrutinized in a confocal light microscopy (shown in Figure 6A and B). The results of the reference examinations attained from the uncoated plate are presented in Figure 7.

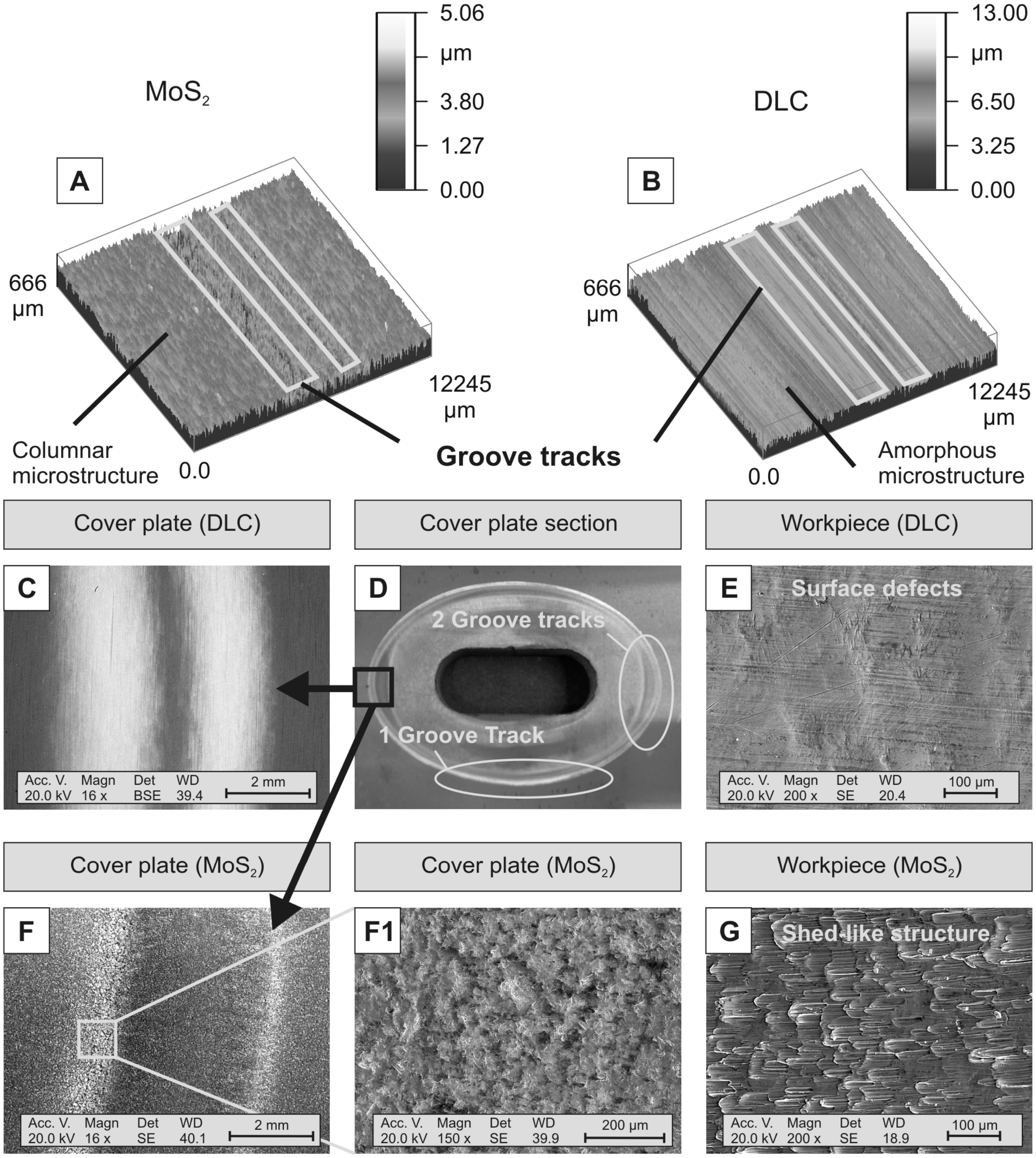


***Figure 6:** Cover plate and workpiece surface taken by SEM and confocal microscopy for DLC and MoS_2 layer systems*

It can be seen that the forming process has different influences on the cover plate as well as on the formed workpiece surface depending on the layer system. The topology of the MoS_2 coated cover plates demonstrates a columnar microstructure of the layer (Figure 6A). The workpiece formed by using a cover plate coated with MoS_2 indicates a shed-like structure on the surface, which reflects the microstructure of the MoS_2 coated cover plate surface (Figure 6G). A reduction of the MoS_2 layer thickness promises for a smoother surface by a high wear resistance [11] The analysis of the DLC layer topology presents a smooth surface (Figure 6B), which corresponds to the amorphous microstructure of this layer [13]. Moderate surface defects by the impact have been observed on the workpiece surface after the EMF by using DLC coated cover plates (Figure 6E). The groove on the DLC coated cover plates presents a width of approximately 2 mm; whereas a width of only 0.5 mm can be detected on the MoS_2 coated cover plates (compare Figure 6C and F). Due to the low friction coefficient and the lubrication effect as well the MoS_2 layer [12] presents a higher resistance against the impact forces occuring by the electromagnetic sheet metal forming process.

A poor wear resistance can be observed on the uncoated cover plate compared to the coated ones. In case of the uncoated cover plate the groove width is approximately 3 mm, even using lubricants (Figure 7).

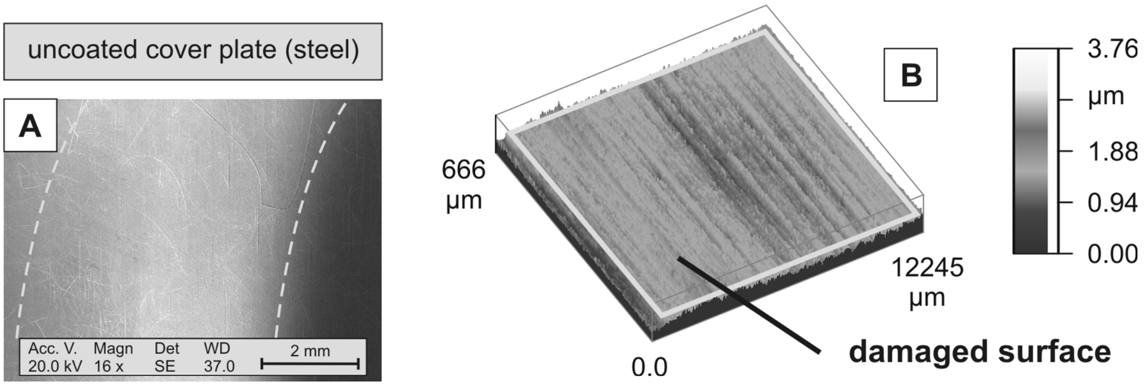


Figure 7: *SEM-image and a 3D-profile of the uncoated cover plate surface*

Based on the attained results the coated cover plates present a better protection potential against the impact forces occurring during the electromagnetic forming than the uncoated cover plates.

3 Summary & outlook

Two promising die concepts for the electromagnetic sheet metal forming process are pointed out in the present paper. One possibility regarding the die design is the target-oriented modification of local stiffness realized in the present investigation by use of geometrical inserts. It could be observed that the occurring geometrical deviations are reduced by increasing the stiffness of the workpiece. Here, it is important to find a balance between the required geometrical stiffness to realize a component and the maximum formability of the used material (e.g. thinning), which are acceptable regarding technical as well as functional requirements. A method to evaluate the feasibility of geometrical details is introduced, which needs to be developed in detail in the future.

The second possibility presented in this paper is the use of coated cover plates in order to increase the lifetime of the stressed parts of the die as well as to prevent the use of lubricants by the electromagnetic forming, which could cause geometrical deviations of the workpiece. For this purpose the different coating systems have been characterized. Based on this, two layers, namely the DLC-layer and the MoS_2-layer, have been chosen for further investigation regarding to their behavior during the electromagnetic sheet metal forming. Although the workpiece was not lubricated during the experiment, no fretting between aluminum workpiece and the coated cover plate could be observed. Moreover, all coated cover plates have shown a better wear and friction resistance compared with the uncoated ones. Further layer optimization will be associated with a significant decline of the wear and impact resistance for high speed forming conditions which are present during electromagnetic forming.

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