Novel Layers for Dies Used in Electromagnetic Sheet Metal Forming Processes [*]

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Abstract

Due to the high forming velocities during electromagnetic sheet metal forming processes, a high impact force acts between workpiece and die. Here, the die surface sustains high damages shown by high wear and galling of the workpiece on the die surface.

To enhance the die lifetime, a novel coating concept based on the PVD (physical vapour deposition) process was developed. In doing so, the hardness and the toughness of the designed layers were varied and adjusted to the demands of AlMg-sheet forming process.

Keywords

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

1 Introduction

The electromagnetic forming (EMF) process is a highly dynamic process using pulsed magnetic fields to form metals with a high electrical conductivity. A typical setup (see Figure 1) consists of a tool coil, a workpiece, and a form defining tool (die). In this case, a modular die consisting of a drawing ring and cover plate is applied.

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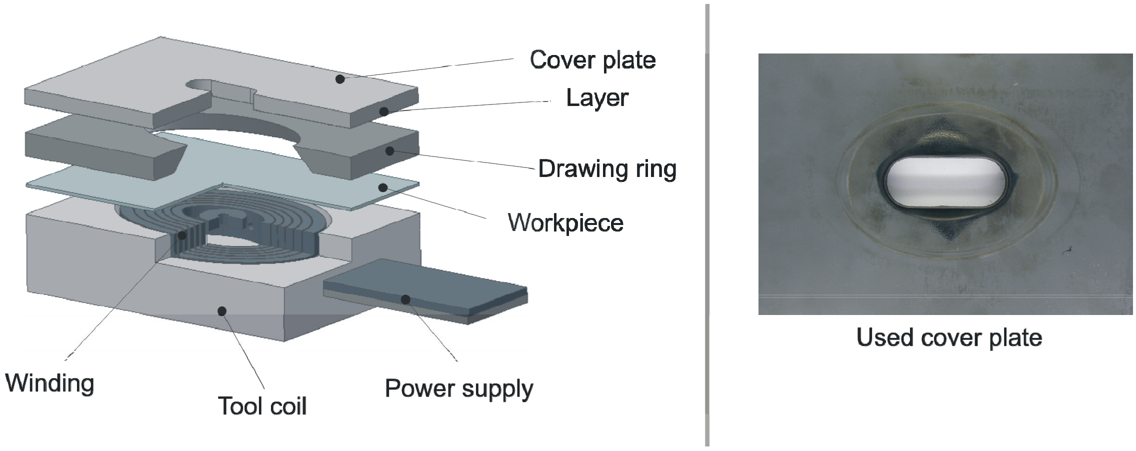
During the deformation the workpiece is accelerated to more than 300 m/s, which reflects the highly dynamic character of the EMF process [1-2]. Here, high contact forces between workpiece and die, or more precisely the cover plate, occur during impact. As a result of the temporarily and locally non-uniform velocity distributions caused by an elliptical tool coil, an oval-shaped imprint can be detected in the area where the workpiece touches the die first and with maximum velocity (see Figure 1). Due to this, the tool surface is exposed to significant wear during the service time because of the high forces associated with large damages as well as deteriorated surface roughness.



Used cover plate

***Figure 1**: Draft of the experimental setup and an exemplary cover plate*

Another aspect of reducing tool lifetime is galling or cold welding – adhesion of sheet metal on the tool surface after forming [3-5]. These effects can be reduced by the application of fluid lubricants, but this can lead to geometrical deviations of the formed workpiece due to the accumulation of the lubricant.

In materials science the trend is targeted at the modification of tool surface with custom-made characteristics for complex requirements [6]. In this regard, the thin film technologies offer a large potential by designing layers with defined structures and tailored-made characteristics [7]. Monolayer, nanostructured layer systems as well as multilayer systems, such as TiAlN, TiN/AlN, TiN/VN, TiN/ZrN etc., exhibit a high potential due to their high hardness of more than 40 GPa [8-10]. In order to be able to use their advantages optimally, the layer's properties must be adjusted to the process features, such as forming velocity, the material to be formed, forming temperature, etc.. Podgornik et al. [11] found out that with the decrease of the tool's surface roughness both friction and tendency to galling can be reduced by cold steel forming. They observed that the carbon-based low friction coatings of DLC (diamond-like carbon) type possess a higher galling resistance compared to the hard TiN coatings. To the same conclusion came Murakawa et al. [12] by deep-drawing of aluminium. Whereas CrN and TiAlN hard coatings improved the dies lifetime up to three times, employing DLC coatings on deep-drawing dies increased the die's lifetime ten times.

In order to enhance the resistance of the forming tool employed by EMF against wear and impact as well as to extend the lifetime of the die, an innovative concept concerning the die surface modification has been developed and will be presented in this research work. In this context, different PVD layer systems have been designed and deposited, in which the hardness and toughness of the layers have been adjusted related to the soft aluminium sheets and high forming velocity. Corresponding metallographic, mechanical, and microscopic investigations of the coated layers have been conducted to understand the relation between layer microstructure and tribological properties. To evaluate the behaviour of the coatings under dynamic impact conditions, which are comparable to the EMF process, a custom-made impact testing device including measurement systems was designed and utilized. Additionally, a finite element simulation was carried out in order to estimate the occurring contact forces between the workpiece and the forming tool. Based on these results, accompanying electromagnetic forming experiments have been performed to establish the correlations between developed layers and real forming conditions.

2 Description of the experiments

2.1 Experimental setups

In this work, two kind of coating systems were designed and deposited - hard and low friction carbon-based layers (DLC) and hard multilayer systems (Ti / TiAlN) containing ten individual layers with different layer thicknesses. Layer depositions were carried out in a high ionization magnetron sputtering PVD-device (CC800-9sionx, CemeCon, Germany). Cylindrical specimens (diameter of 40 mm and thickness of 12 mm) of tempered steel (1.3502) were employed as substrates and were used to analyze as well as to optimize layer systems related to the electromagnetic forming process demands. Prior to the coatings the specimens were polished up to 1 µm and cleaned in an ultrasonic bath with acetone for 15 min. The last cleaning treatment occurred in the PVD-device during etching, where the substrates surfaces were activated at the same time to enhance the adhesion between substrate and coatings. In order to deposit DLC-layers, two carbon and two chromium targets were employed in a pulsing mode and C_2H_2 atmosphere. Thereby, bias-voltage was varied to adjust the features of carbon-based layers to electromagnetic forming process demands. For $(Ti/TiAlN)_5$ layers one Ti target and three TiAl 60:40 targets were sputtered in inert atmosphere to deposit Ti-layers and in nitrogen atmosphere to deposit TiAlN-layers. In doing so multilayers with varied Ti monolayer thickness from 10 to 100 nm and constant TiAlN layer thickness with approx. 500 nm were analyzed regarding their capability of being adjusted to EMF. The best adjusted layers were deposited on cover plates (diameter of 120 mm and thickness of 12 mm) to investigate the improvement of galling resistance. The deposited layers and PVD deposition parameters are summarized in Table 1.

The layer thickness and morphology were investigated by means of SEM (JXA840, JSM 35, Japan). The layer adhesion was analyzed by means of scratch tests with a maximum load of 100 N. A ball-on-disk tribometer (CSEM, Switzerland) was employed to test the friction and sliding wear characteristics of the layers. The tests were performed using a WC-Co ball (1880 HV0.1) with 6 mm diameter and a load of 5 N with a constant track speed of 0.4 m/s. The layer hardness and Young’s modulus were acquired by nanoindentation tests (NANO indenter XP, MTS Nano Instruments, USA).

Coating systems	**DLC**	**Ti**	**TiAlN**
Thickness	ca. 3 µm	10-200 nm	ca. 500 nm
Deposition Parameters			
Etching	650 V, 240 kHz, 200 mln Ar, 50 mln Kr, 45 min		
Cathode number	4 (2 Cr; 2 C)	1	3
Gas	Ar, Kr, C_2H_2	Ar, Kr	Ar, N_2
Power [W]	4000	4000	5000
Bias-Voltage [V]	25-150	100	100
Mode	Pulsing	DC	DC

Table 1: *Coating parameters.*

To evaluate the behaviour of the coatings on the EMF process, a custom-made impact tester (see Figure 2) with a velocity of 30 m/s was utilized (see [4]). A ball is fixed on the plunger and this plunger- unit is positioned at the upper end of the acceleration pipe. The test is started by dropping the plunger unit. In order to achieve velocities up to 25 m/s, which are higher than those realized by gravity (approx. 10 m/s), an additional pressure supply can be used. At the lower end of the acceleration tube the upper plunger is suddenly stopped by an anvil, where the specimen is located. In order to determine the fall velocity, a light barrier, which is integrated in the using the effect of shadowing a light beam, is applied.

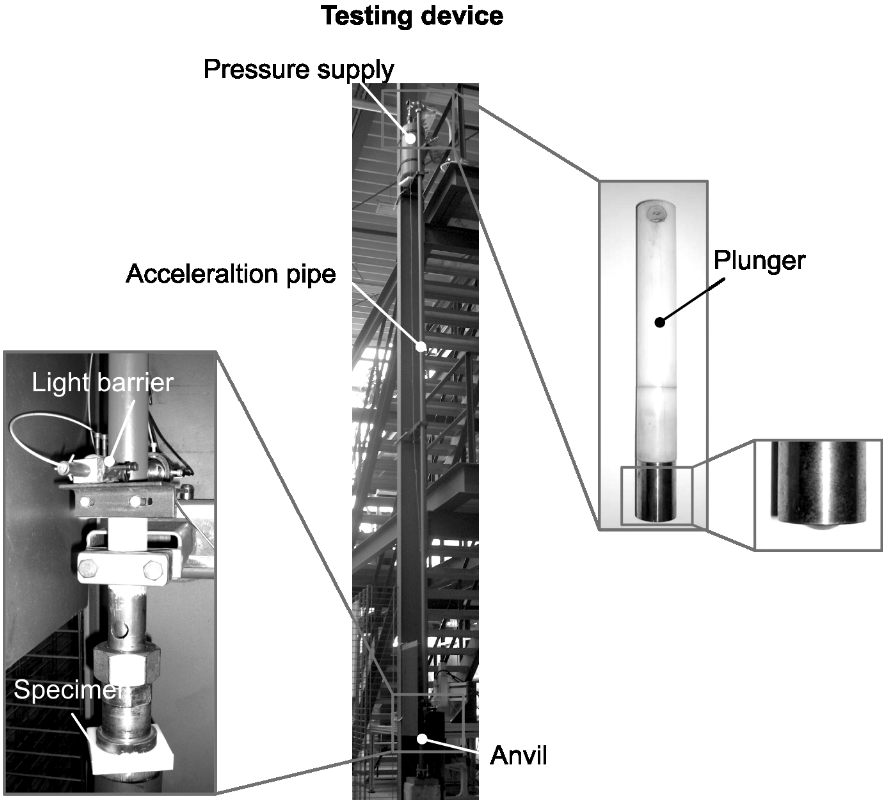


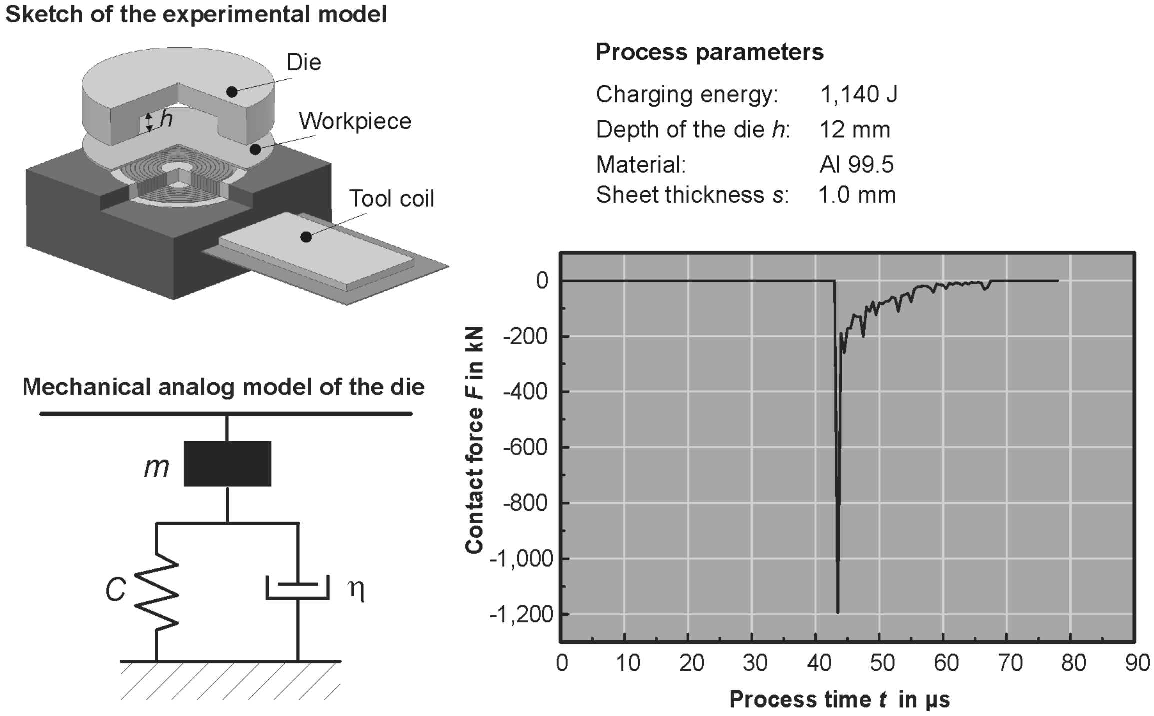
Figure 2*: Impact testing device*

The surfaces of the tested samples were analyzed by an optical 3D-profilometer (Infinite Focus, Alicona Imaging GmbH, Austria). Aimed to investigate the designed coating in the EMF process, 40 forming processes were carried out in a pulse generator device (Maxwell Magneform 2000, USA) with a charging energy of 2.560 J, inductance of 44 nH, capacity of 960 µF, and an eigenfrequency of 23 kHz. The setup is shown in Figure 1. The employed workpiece material was an aluminium alloy AlMg3 with a thickness of 1 mm and nearly pure aluminium Al99.5 with a thickness of 2 mm.

2.2 Analyzing method to estimate the impact force

An experimental setup for estimating the contact force between workpiece and die is really difficult. On the one hand the sensors, have to bear a high and short impact and, on the other hand, the design implementation of the sensor into the die is quite complex. Therefore, the finite element analysis (FEA) is used to estimate the acting contact force during the forming process.

A mass-spring-damper system is implemented into the structure-mechanical simulation instead of a meshed die to represent the die's physical behaviour. The chosen arrangement of the elements of the mechanical analog model influences the response behaviour of the model. A first approach is a parallel connection of the damper and the spring (Kevin-Voigt-Model) to which the substitute mass is connected in series (see Figure 3).



Process parameters

Charging energy:	1,140 J
Depth of the die *h*:	12 mm
Material:	Al 99.5
Sheet thickness *s*:	1.0 mm

Figure 3: *Mechanical analog model: "Mass-Spring-Damper"*

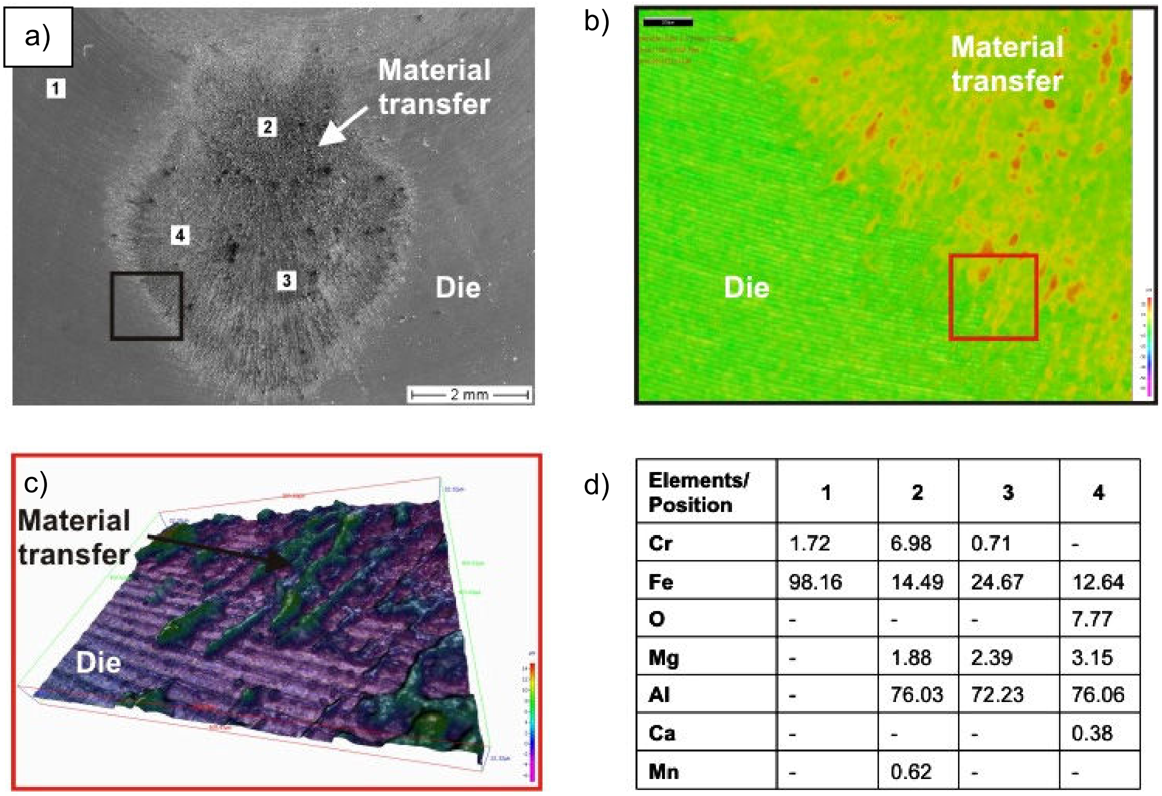
The stiffness of spring *C* represents both, the material stiffness (Young's modulus) as well as the geometrical stiffness (e.g. the height of the die). In the same way the damping coefficient η represents the material damping property as well as the constructive change, such as the use of an additional shock absorber. The mass *m* within this model could be calculated based on the die geometry. The mechanical analog model as well as an exemplary force distribution established by the described model in a FEA is displayed in Figure 3 together with the simulation parameters used.

This diagram shows the qualitative trend of the contact force between workpiece and die. It can be clearly seen that the force impact reaches 1.2 MN for a short period of time. This is important with respect to the coated cover plates, which have to sustain this impact.

3 Results and discussion

3.1 Damages of uncoated tools

Typical damage tool surfaces being exposed to very high contact forces, where the counterpart material was a AlMg3-alloy, are shown in Figure 4. At the radius of the contact zone between die and workpiece a material transfer with a thickness of approximately 20 µm was detected.



Elements/ Position	1	2	3	4
Cr	1.72	6.98	0.71	-
Fe	98.16	14.49	24.67	12.64
O	-	-	-	7.77
Mg	-	1.88	2.39	3.15
Al	-	76.03	72.23	76.06
Ca	-	-	-	0.38
Mn	-	0.62	-	-

Figure 4: *a) SEM- , b)-c) 3D-profilometer and d) EDX-analysis of damaged tool*

EDX-analyses of these areas indicate the existence of Al and Mg, which support the galling phenomena during the forming process. AlMg3 alloy sheets are exposed to high pressures and velocities employed on the forming process leading to cold welding between workpiece and tool surface [13]. Springback effects tear apart the cold welded areas. The consequences are grave formation and fretting wear of both tool and workpiece [14].

3.2 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 investigated with standard tests. SEM images of coatings fracture surfaces reveal a good adhesion between substrate and coatings as well as a good cohesion within the layers for all systems (Figure 5). Dense structures for all coatings were observed. While a textured columnar morphology was detected in the multilayer systems, amorphous, "glassy" structures were found for carbon-based coatings.

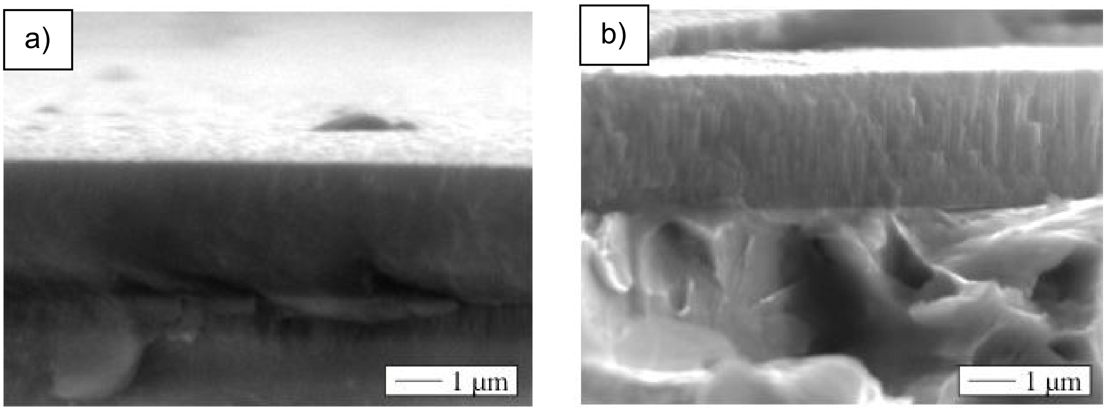


***Figure 5**: SEM images of a) DLC-coating and b) Ti/TiAlN multilayer*

The hardness and Young's modulus of the deposited layers are presented in the Figure 6. It is observable that by reducing the metallic monolayer thickness the hardness of the Ti/TiAlN multilayers was increased, whereas the Young's modulus did not change. Consequently, the layer toughness remained constant by an increase of the layer hardness. Bemporad et al. [15] and Evans et al. [16] found a rise in the hardness and adhesion through a reduction of the metallic layer thickness within the multilayer systems due to a better interface toughness and lower residual stresses. This explains the improved adhesion of multilayers with reduced metallic layer thickness.

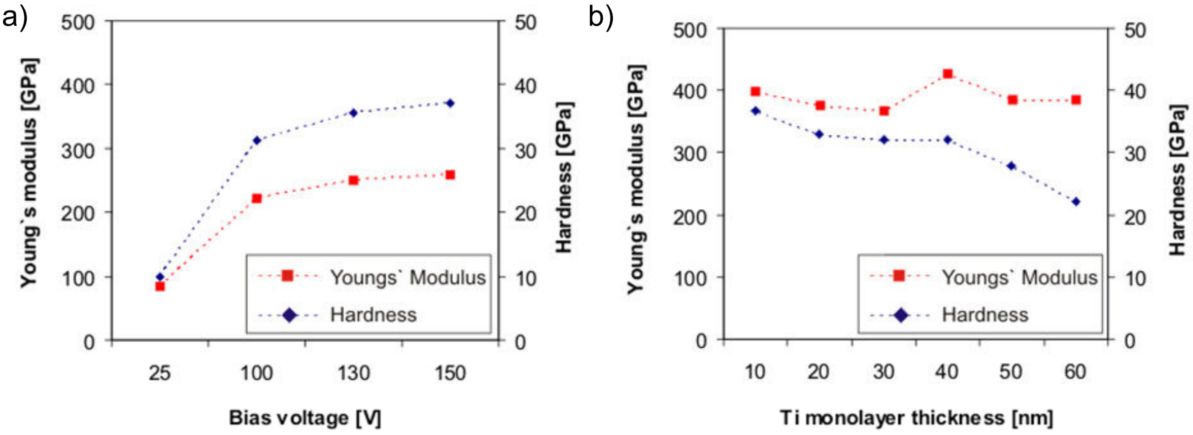


***Figure 6**: Young`s Modulus and hardness results of a) DLC-coating and b) Ti/TiAlN-multilayer*

A hardness improvement of approximately 4 times was detected fore DLC layers by increasing the bias voltage from 25 to 150 V. This leads to a higher Young`s modulus and thereby higher stiffness of the DLC-layers. However, the Young’s modulus of DLC coatings is lower (max. 250 GPa) compared to the Ti/TiAlN multilayers (min. 380 GPa), which supports a higher toughness of DLC coatings compared to the Ti/TiAlN multilayers.

Figure 7 compares friction coefficients as well as the progress of abrasive behaviour of both layer systems in a sliding test. It is obvious that the mechanism of layer failure is different. DLC coatings wore slowly. The initial friction is higher than 0.2, but reduces very quickly to remain stable at 0.05 for all deposited DLC coatings and is independent from the applied bias voltage. On the contrary, Ti/TiAlN-multilayers show a progressive wear associated with high friction coefficients. This is in accordance with further studies [18], where low friction coefficient values for DLC coatings were explained with the existence of graphite as lubricant film.

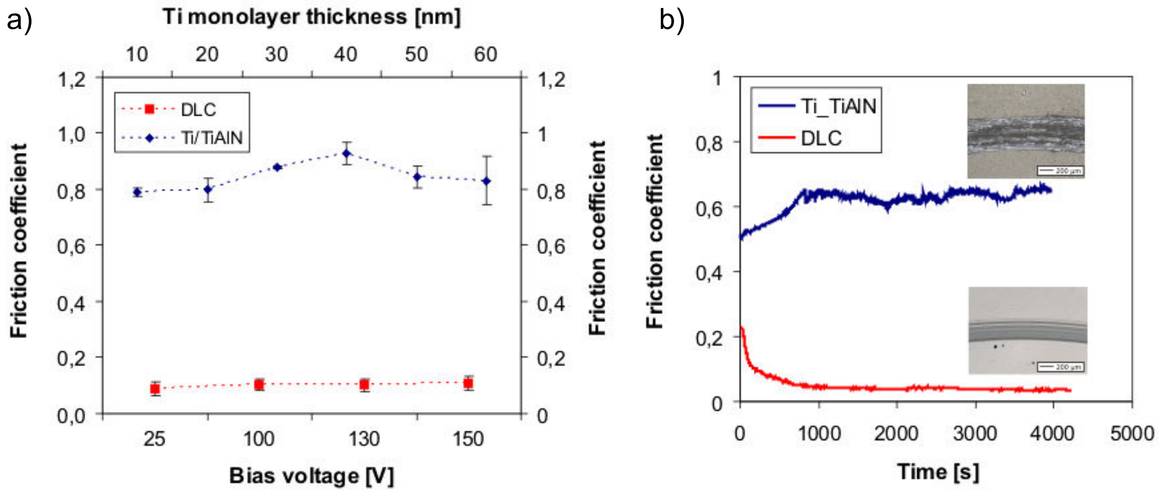


***Figure 7**: a) Friction coefficient and progress of abrasive behaviour of deposited coatings*

Figure 8 shows the different failure modes of the coated samples in scratch tests. Since DLC coatings possess a high portion of graphite an acoustic measurement during scratch tests is more difficult than for Ti/TiAlN multilayers.

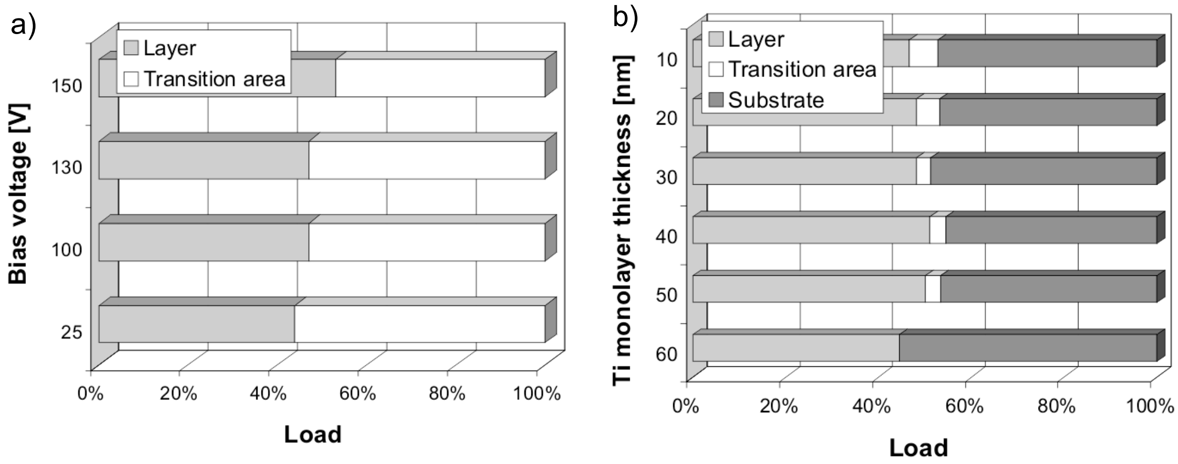
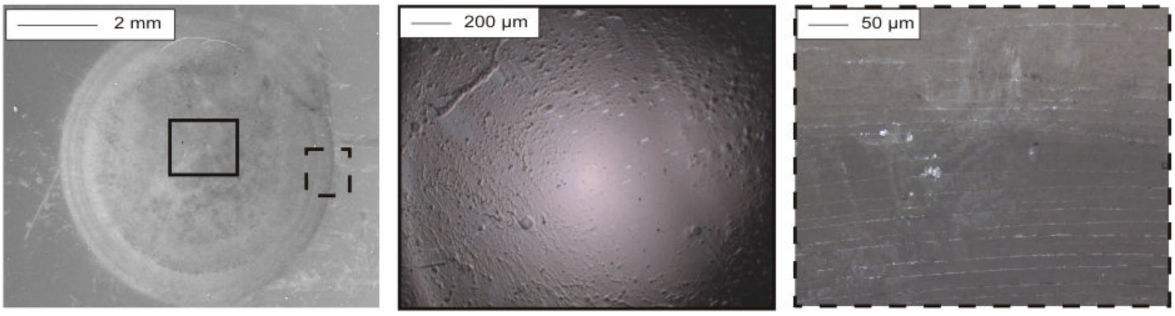


***Figure 8**: Adhesion results of a) DLC coatings and b) Ti/TiAlN multilayers*

Graphite in the DLC coatings lubricates and does not chip off. Under the optical microscope a large transition area between the cracking of DLC coatings and substrate was observed. Thereby the exact failure position, and thus the critical load, could not be determined. However, the first critical load L_{C1} for both systems is in the same range between 40 and 50 N. Scratch tests on DLC-coatings showed no debonding up to loads of 100 N. In contrast to that, multilayer systems had a small cracking transition zone between the first layer and substrate. This area was enlarged by decreasing the Ti monolayer thickness. These results clearly indicate that the DLC coatings are harder and tougher than the Ti/TiAlN mutlilayers, whereas in Ti/TiAlN multilayers both hardness and toughness are enhanced by decreasing the Ti monolayer thicknesses.

Additional tests with the custom-made impact device, shown in Figure 2, were performed on Ti/TiAlN multilayers to evaluate them under EMF process conditions. None of the layers shows macrocracks or spallations, even though all tested systems could not eliminate a plastic deformation of the substrate materials (Figure 9).

Ti/TiAlN multilayers with a thick Ti monolayer



Ti/TiAlN multilayers with a thin Ti monolayer

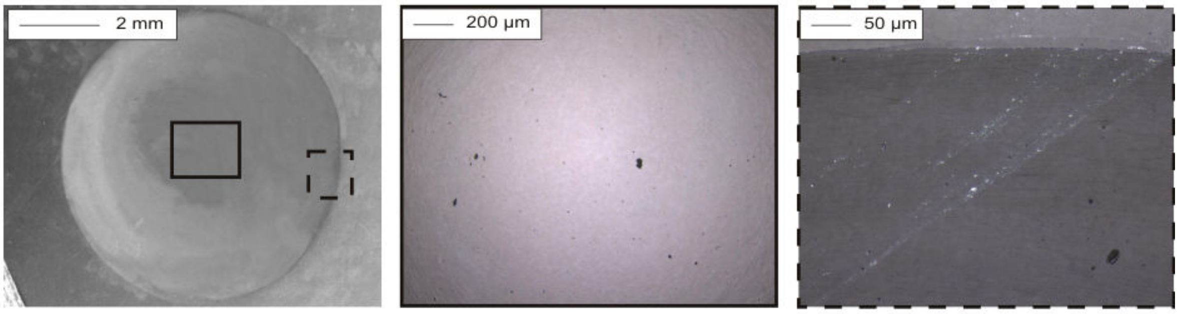


***Figure 9**: Impact test results*

The plastic deformations had a diameter of 3.1 to 3.6 mm and a depth of 0.3 to 0.5 mm. The high resistance against this impact test indicates a high adhesion of multilayers on tempered steel and a high cohesion within the multilayers. It is noteworthy that the thinner the Ti monolayers are the larger is the resistance of the systems against impacts.

Based on the results taken from standard tests it can be established that DLC coatings deposited at high bias voltage and Ti/TiAlN layer systems with 10 nm Ti monolayer thickness show the best performance. Therefore, dies were coated with these systems and evaluated in the EMF process.

3.3 Forming experiments employing coated tools

Dies coated with DLC and Ti/TiAlN multilayer systems were firstly investigated during electromagnetic forming of aluminium sheets after 40 impacts (Figure 10). The characteristic round groove was detected in both dies, while no fretting wear was found. 3D profilometer analyses of these areas show a light damaging in the form of wear of coated die surfaces. These damages are higher for Ti/TiAlN than for DLC coated die. This can be explained by the lower friction coefficient of DLC layers compared to Ti/TiAlN multilayers, which thereby improve the wear resistance of dies. To the same conclusion came Podgornik et al. [13] by cold forming of austenitic steels.

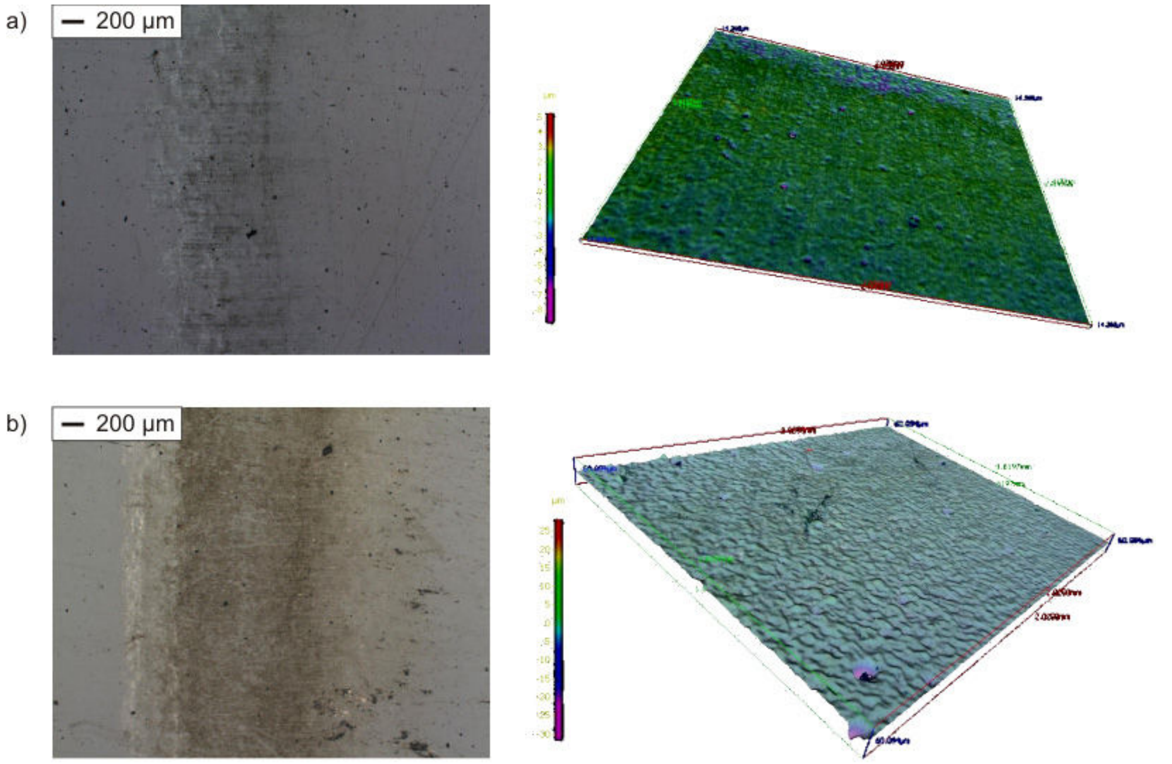


***Figure 10**: 3D profilometer analyses of a) Ti/TiAlN and b) DLC coated die in real and false colours after forming of Al-sheets*

When forming AlMg3 alloy sheets next to round grooves the fretting wear on coated dies was observed. The thickness of material transfer varied from 2 µm for Ti/TiAlN coated dies to only 1 µm for DLC coated dies (Figure 11). Based on the results attained, the fretting wear was reduced approximately 10 to 20 times by employing coated dies (see chapter 3.1). However, it is noteworthy that AlMg3 sheets cause more damages on dies than Al sheets.

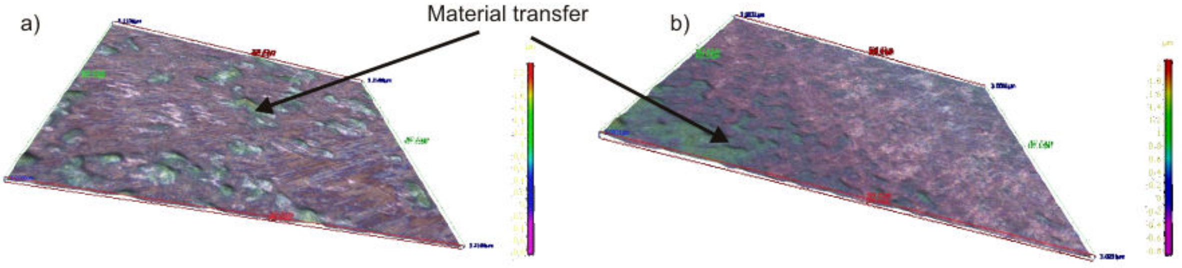


Figure 11: *3D profilometer analyses of a) Ti/TiAlN and b) DLC coated die in false colours after forming of AlMg3 sheets*

4 Summary & outlook

In this research work an approach to enhance the galling resistance of dies employed by electromagnetic forming processes was presented. Two different kinds of coatings - low friction DLC layer and Ti/TiAlN multilayers - were studied and adapted to the EMF process demands. It was detected that the DLC layers feature lower friction coefficients at high hardness and lower Young's modulus than the Ti/TiAlN multilayers, while the hardness of the multilayers increases when reducing the Ti monolayer thickness by a constant steady-state Young's modulus. Based on the level of Young's modulus, DLC layers have a higher ductility than Ti/TiAlN multilayers. Consequently, the hardest DLC layer and Ti/TiAlN multilayer with the thinnest Ti monolayer (10 nm) were chosen for further investigation in the EMF process. Coated dies show no galling after forming Al sheet, while after forming AlMg3 sheets a slight material transfer was observed. However, the galling resistance for both coated dies was enhanced compared to the uncoated ones. The wear resistance of DLC coated dies was higher than the Ti/TiAlN coated dies independently of the materials to be formed.

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