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RESEARCH

Wear Behavior of Uncoated and Coated Tools under Complex Loading Conditions

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A B S T R A C T

In automotive industry crash relevant structures of the body in white are manufactured using the direct hot stamping process. Due to the high temperature difference between the hot blank and the cold tool surfaces and the relative movement between the blank and the tool surfaces during the forming operation, high thermal and mechanical loads are applied on the tool leading to excessive wear in terms of adhesion on the tool surfaces. One possibility to reduce wear of hot stamping tools is the application of tool coating systems. In the scope of this work uncoated and coated tools are characterized under complex loading conditions with respect to adhesive layer build-up.

1. INTRODUCTION

Nowadays light weight design of the body in white is not only achieved by a substitution of conventional steel grades with light weight materials such as aluminum and magnesium alloys but also by manufacturing structural components out of high strength steel grades. Due to the increase of materials tensile strength a reduction of the sheet thickness of the component is possible attended by a weight reduction with steady or even increased components strength [1]. These steel grades can be processed by direct hot stamping which can be described as forming and quenching in one process step (Fig. 1). Due to the high temperature difference between the hot blank and the cold tool surfaces and the relative movement between the blank and the tool surfaces during the forming operation, high thermal and mechanical loads are applied on the tool.

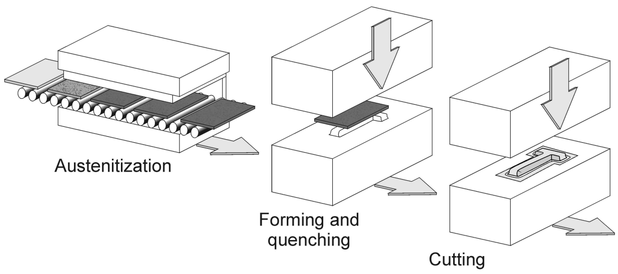

Fig. 1. Schematic figure of the direct hot stamping process.

Excessive wear can be observed on the tools used for direct hot stamping as a result of these load cases. To avoid decarburization and scaling during austenitization, semi-finished products with an aluminum silicon pre-coating are used. This pre-coating also supports the occurrence of wear in terms of adhesive layer build-up by an increasing number of drawn components leading to degradation of material flow and workpiece accuracy. Time consuming and expensive rework has to be done to remove the layer build-up and to ensure the components quality [2].

Due to their excellent properties, such as a high hardness of up to 3200 HV0.05 and a maximum temperature of service of up to 1100 °C, AlCrN-tool coating systems came into consideration to be applied on tools used for direct hot stamping. Compared to conventional Ti-based coatings, AlCrN-coating systems have a higher hardness and a better resistance against oxidation and wear [3, 4].

Within the scope of this work adhesive wear behavior of aluminum silicon pre-coated boron-manganese steel is investigated under process relevant conditions. Thus, a tool was designed based on a sheet-bulk metal forming process to enhance adhesive layer build-up due to its more complex loading conditions. By sheet-bulk metal forming a cold bulk metal forming operation is applied on sheet metal to form complex geometries out of the sheet as under investigation for synchronizer rings in [5]. Compared to sheet metal forming the sheet-bulk metal forming process has the characteristics of higher contact pressures and varying stress conditions on the tools surfaces, leading to higher normal loads and thus to faster initiation of adhesive wear. Combined with a subsequent quenching operation of the austenitized blank in the tool higher components strength can be achieved as by utilizing strain hardening of the cold forming operation. The tests are conducted using uncoated and AlCrN-coated tools. Adhesive wear on both, uncoated and coated tools is analyzed two-dimensionally using tactile stylus measurement and three-dimensionally with confocal microscopy. Via comparing worn and unworn die surfaces the wear evolution can be determined. Furthermore the possibility of reducing wear by using AlCrN-tool coating systems will be shown.

2. INVESTIGATED WORKPIECE AND TOOL COATING MATERIALS

The normally used steel grade within direct hot stamping is a 22MnB5 with an aluminum silicon pre-coating. In its initial state the semi-finished product has a fine grain ferritic-pearlitic microstructure with a good formability and a yield and tensile strength of about 400 MPa and 600 MPa respectively. The increase in yield and tensile strength up to 1100 MPa and 1600 MPa is achieved by a heat treatment and a subsequent quenching operation. The heat treatment is carried out at a temperature above the specific Ac_3 temperature of about 850 °C and is required to achieve the microstructural phase transformation to austenite. Within the subsequent quenching operation the cooling rate of the hot blank has to exceed 27 K/s to guarantee a fully martensitic grain structure. Also the pre-coating of the blank passes through several phase changes during the heat treatment. This is a result of temperature driven diffusion processes of the iron from the base material into the aluminum silicon layer, increasing the melting point of the coating to a temperature of up to 1100 °C [6]. A maximum heating rate of 12 K/s to 15 K/s should not be exceeded to avoid melting of the aluminum silicon coating at a temperature of about 620 °C [7]. Different zones in the aluminum silicon coating develop depending on the dwell time in the furnace [8]. But an increase in dwell time also causes a homogenizaiton of the aluminum silicon layer attended by a coarsening of the layer surface and an increase of layer thickness leading to a degradation of weldability. Due to the diffusion of iron into the coating hard intermetallic Fe-Al-Si emerge, leading to an increase in wear on the tool surfaces in terms of grooves and adhesive layer build-up on the tool.

Due to its properties like a maximum service temperature of up to 1100 °C and a hardness of 3200 HV 0.05, an AlCrN-monolayer tool coating system is investigated. This coating system is applied by Physical Vapour Deposition (PVD) on the tool material and has a thickness of 3.4 μm measured by ball grinding tests. In [9-11] both, thermal and tribological properties of this coating system were characterized showing no degradation of these properties when used on tools for the direct hot stamping process.

To investigate wear behaviour on the tool surfaces both uncoated and coated tools are used. Representing standard steel used for warm forming tools the steel grade 1.2367 in its uncoated condition and with applied AlCrN-monolayer coating was chosen for these experiments.

3. EXPERIMENTAL PROCEDURE

A new experimental sheet-bulk metal forming tool was developed for wear experiments to achieve complex load conditions on the tool surfaces. Sheet-bulk metal forming can be described as application of bulk metal forming processes, such as upsetting, on sheet metal semi-finished products [12]. Within this tool a blank with an initial sheet thickness of s_0 = 4.5 mm, an outer diameter of d_{outer} = 39 mm and an inner diameter of d_{inner} = 13 mm is formed to the geometry shown in Fig. 2.

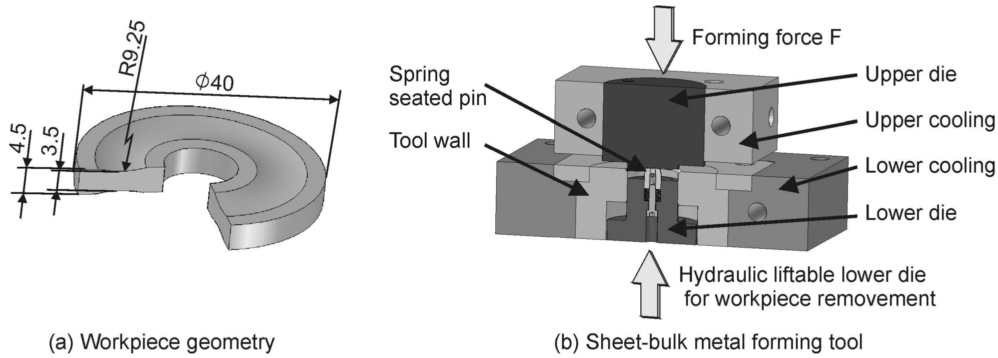

Fig. 2. Workpiece geometry after forming and sheet-bulk metal forming tool.

Due to the lack of aluminum silicon pre-coated boron manganese steel sheets with a thickness over s = 2.5 mm, three blanks of on initial sheet thickness of s = 1.5 mm are stacked to reach a blank thickness of s_0 = 4.5 mm. A dwell time of t_γ = 6 minutes was chosen due to the higher thickness of the blank to guarantee a homogenous temperature distribution for the austenitization of the blank at an austenitization temperature of T_γ = 950 °C. To achieve a thinning in the middle area of the workpiece geometry to s = 3.5 mm both, the upper and lower die have a circular radius of r = 9.25 mm. Thus, a material flow out of this area into the inner and outer cavity is obtained. The pre-hole of the initial blank is used for centering the hot sheet stack onto a spring seated pin. The liftable lower die relieves the removal of the workpiece after forming and quenching in its upper position by providing enough clearance.

The experiments were carried out using uncoated and coated dies with a total amount of 50 strokes each. Wear evolution of both tool sets is compared by tactile stylus measurements and confocal microscopy after every 10 strokes.

4. RESULTS AND DISCUSION

By using this new sheet-bulk metal forming test setup high contact pressures are applied on the tool surfaces, leading to the initiation of adhesive layer build-up on the tool surfaces. To calculate these high contact pressures the experiment is also simulated using the finite element software ABAQUS 6.9 EF1. Via comparison of the punch force of the experiment and the calculation, the numerical model is calibrated. Thereby a maximum punch force of 328 kN in the experiments is reached, which is in sufficient accordance with the calculated maximum punch force of 330 kN. In Fig. 3 the distribution of the contact pressure p_c along the die geometry at the moment of the maximum punch force is shown.

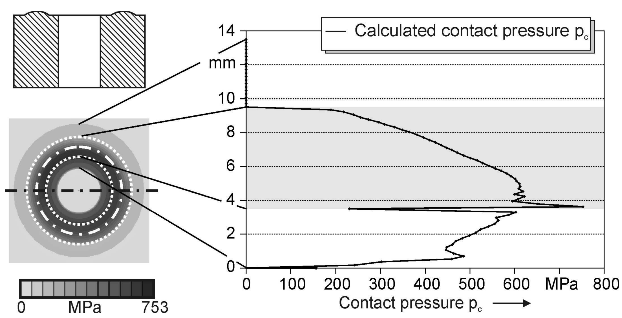

Fig. 3. Calculated contact pressure p_c on the lower sheet-bulk metal forming die.

It can be noticed that the highest contact pressure of $p_{c,max}$ = 752 MPa is located at the runout of the inner die radius followed by a immediate decrease in the transition to the inner surface. This is a result of material flow into the inner area of the die where it is pressed into a smaller volume of the cavity leading to this peak in contact pressure. In the direction of the outer die radius a constant decrease in contact pressure can be seen. On the outer die surface no contact pressure is applied due to the absence of contact between tool and workpiece. In this area the material flows into a greater volume with the effect of a spreading of the material until a contact with the tool wall is achieved.

With the new developed sheet bulk metal forming tool wear experiments with uncoated and AlCrN-coated dies were carried out with up to 50 strokes each. After every 10 strokes the arithmetic mean roughness R_a is determined by tactile stylus measurements. The roughness evolution of the inner surface, the outer surface and the surface on the radius of the uncoated lower die is shown in Fig. 4.

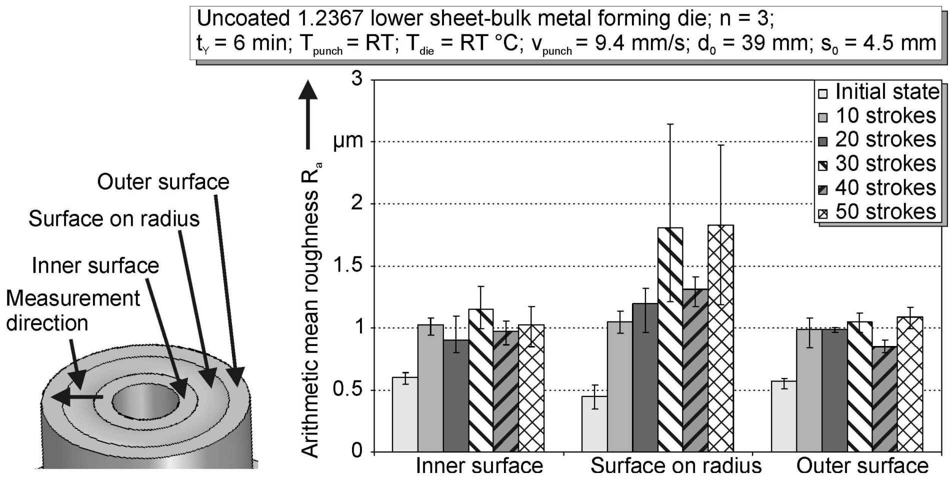

Fig. 4. Evolution of roughness on the uncoated lower sheet-bulk metal forming die.

It is obvious that on all three measurement points an increase in arithmetic mean roughness R_a after the first 10 strokes can be seen. The roughness nearly doubles and keeps at a constant value of about 1 μm on the inner and outer surface. On the surface on the radius a trend of a further increase of roughness can be noticed within 50 strokes. Furthermore the high scattering of the arithmetic mean roughness R_a can be interpreted as some debris which matures on the surface during the experiments.

Fig. 5 shows the roughness evolution of the AlCrN-coated lower sheet-bulk metal forming die. First to notice is the slight roughness decrease on the inner and outer surface and the slight increase in arithmetic mean roughness R_a on the radius after the application of the coating. Like on the uncoated die also an increase in roughness on the coated tool after the first 10 strokes can be determined. But this increase in roughness is less compared to the coated die. On the radius similar values of the arithmetic mean roughness R_a are obtained during 50 strokes.

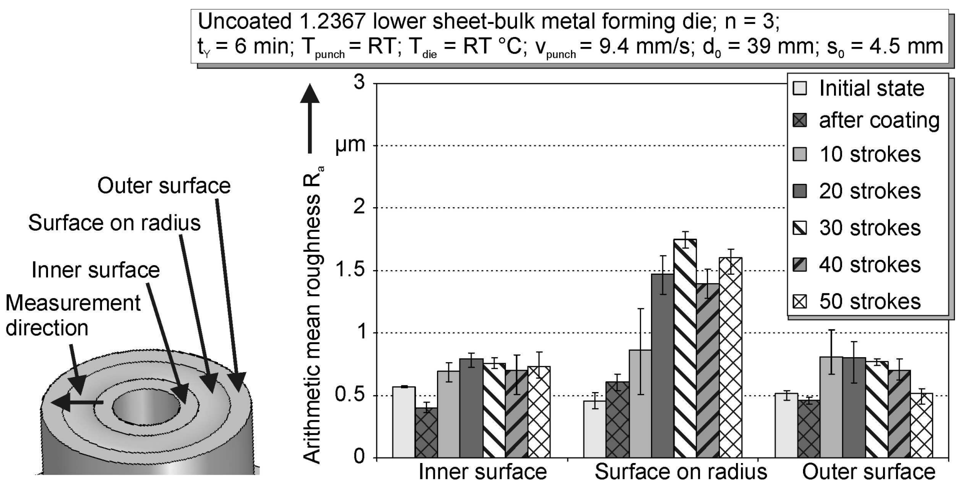

Fig. 5. Evolution of roughness on the AlCrN-monolayer coated lower sheet-bulk metal forming die.

To get further information of the reason for the roughness increase on the different measurement points microscope images of the die surfaces were taken. In Fig. 6 the surface of the uncoated die along the radius after 50 strokes is compared to its initial condition.

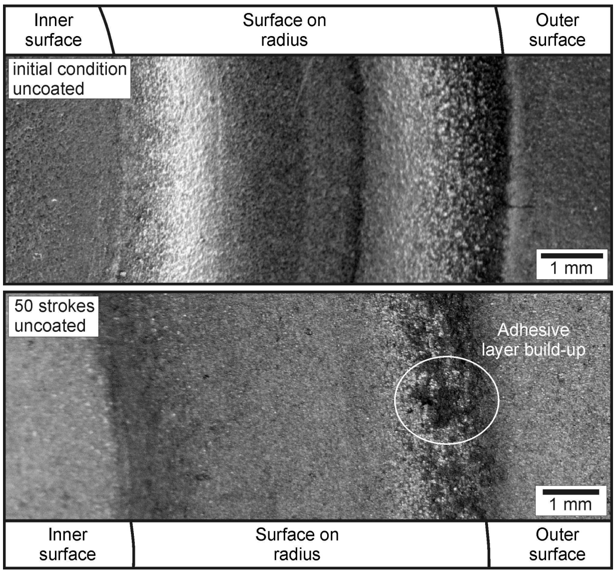

Fig. 6. Adhesive layer build-up on the uncoated lower sheet-bulk metal forming die.

Noticeable is debris adhered on the outer die radius. This build-up is protruded, caused by adhesion of the aluminum silicon coating of the sheet. Also on the outer surface small adhesions can be noticed in terms of darker marks. This means that also in this area the workpiece had contact with the die surface leading to the measurable roughness increase. In the area of the highest contact pressure p_c, at the inner die radius, only slight circular adhesion marks can be seen. In the area of the inner surface on the lower die the material is only touching the die surface with marginal relative movement so that only little aluminum silicon coating of the sheet is sheared off.

In Fig. 7 microscope images of the AlCrN-monolayer coated tool after 10 and 50 strokes are shown. On the outer die radius first changes of the surface can be noticed after 10 strokes in terms of adhesion of the aluminum silicon coating. This adhesion shows a glossy but rough structure under the microscope. This adhesion initiates further layer build-up which can be noticed as darker debris along the outer radius. As seen for the uncoated die also the coated one show only slight circular adhesion marks on the inner radius. On the inner and outer surfaces of the die nearly no adhesion of the aluminum silicon coating can be noticed after 50 strokes.

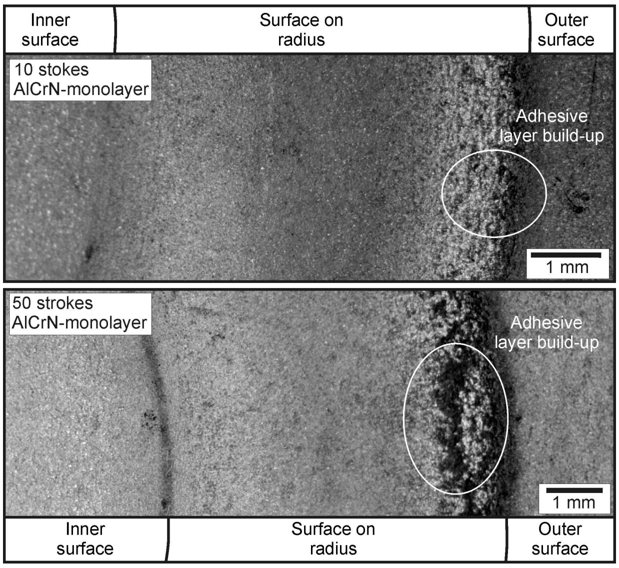

Fig. 7. Adhesive layer build-up on the AlCrN-monolayer coated lower sheet-bulk metal forming die.

The adherence of aluminum silicon coating is not only noticeable on the die surfaces but also on the workpieces. In Fig. 8 SEM-images of the coating of the workpiece are shown. In the area of the inner radius circular cracks develop during the forming operation showing the glossy inside of the aluminum silicon coating.

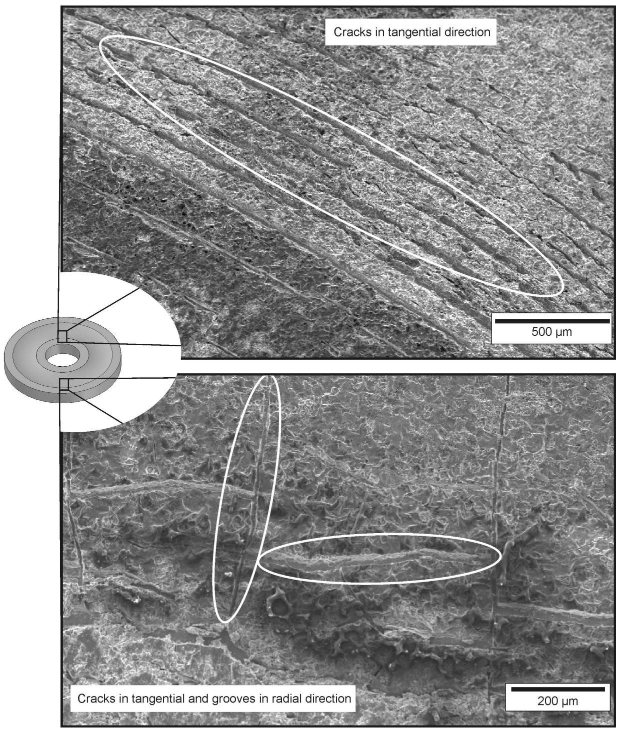

Fig. 8. Crack formation of the aluminum silicon coating on the workpiece.

These circular cracks go around the whole surface as a result of radial tensile stresses in the coating cracking up the surface. Towards the bottom of the radius the amount of these cracks decreases. This can be also noticed in the area of the outer radius based on the same stress conditions. In the inner area no circular cracks develop due to the compression of the material. In the outer area the circular cracks switch to radial cracks towards the outer border. This arises from tangential tensile stresses on the material in that area leading to a spreading of the workpiece material.

Additionally the uncoated and coated die surfaces were measured three-dimensionally by confocal microscopy after 20 and 50 strokes and analyzed. Thus, all surfaces are aligned with a second-degree polynomial to adjust the curvature of the radius (Figs. 9 and 10).

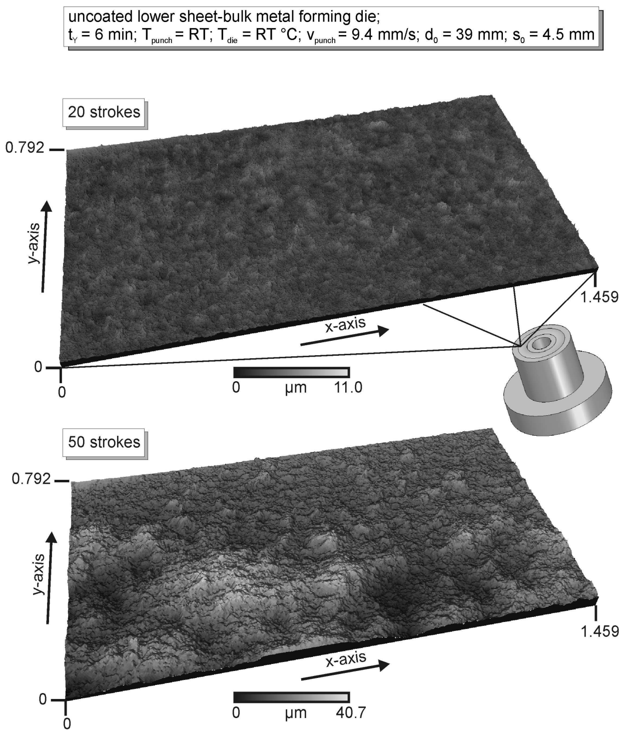

Fig. 9. Adhesive layer build-up on the uncoated lower sheet-bulk metal forming die.

The comparison of the surfaces after 20 strokes shows nearly the same surface roughness S_a of about 1.36 µm for the uncoated and 1.28 µm for the coated die. But it can be seen that there is slightly more build-up on the surface of the coated die as on the uncoated one. This build-up rises higher than on the uncoated surface. To give a first qualitative statement of the amount of adhered aluminum silicon on the die surfaces the material volume of the layer build-up is calculated. A material volume on the uncoated surface of 6943.8 mm^3/m^2 can be determined whereas on the coated one the material volume averages 5741.6 mm^3/m^2. By ongoing strokes more and more adhesion develops on both die surfaces leading to accumulations of build-up. This can be also stated in the increase of surface roughness S_a of 5.32 µm on the uncoated surface and 3.35 µm on the coated surface. Also the material volume on both surfaces increases to 24574.5 mm^3/m^2 for the uncoated surface and 17191.5 mm^3/m^2 for the coated one. The aluminum silicon layer build up on the uncoated surface is not only more protruded but also more homogenous over the surface.

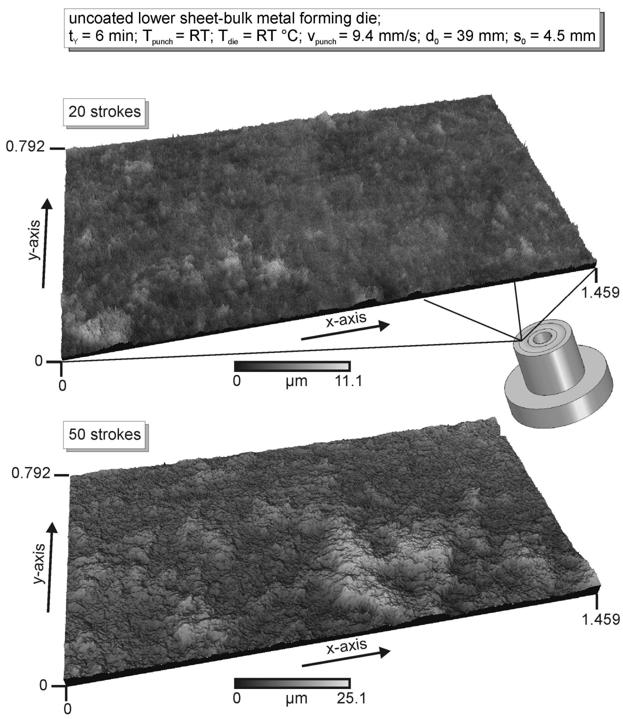

Fig. 10. Adhesive layer build-up on the AlCrN-monolayer coated lower sheet-bulk metal forming die.

5. CONCLUSION

By processing aluminum silicon pre-coated semi-finished products within the hot stamping process automotive industry has to deal with wear in terms of adhesive layer build-up on the tool surfaces. Expansive and time consuming rework has to be done on the tools to remove adhesion and ensure components quality. Within the scope of this work adhesion evolution on tool surfaces is examined. Therefore a new test setup was developed according to a sheet-bulk metal forming process. Following the time-temperature-profile of the hot stamping process wear experiments were carried out using uncoated and AlCrN-monolayer coated tools. After every 10 strokes the roughness evolution on the die surfaces was measured both, two-dimensionally by tactile stylus measurements and three-dimensionally by confocal microscopy. On both, uncoated and coated dies a roughness increase after the first 10 strokes was noticeable. After 50 strokes it was shown that the roughness increase on the coated die is less in areas with low sliding distance and low contact pressures respectively. No difference in roughness increase can be seen on the die radius on both tools. This roughness increase is a result of adhesive wear of the aluminum silicon coating on the die surfaces which is shown in microscope images. They also show that only marginal adhesion develops at the area of the highest contact pressure in contrast to adhesive build-up which develops at areas with long sliding distances and high contact pressures. This first adhesion initiate's further wear which accumulates on the surface. Microscope images of the workpiece show a cracking of the aluminum silicon coating due to the local stress conditions during forming. Based on the experiences of this test setup a new tool will be designed and tested in pre-series in automotive industry. Thereby the blank thickness will be further increased and the workpiece geometry will be more complex. With that tool wear in terms of adhesive layer build-up will be analyzed under industrial conditions.

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