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Analysis of tribological behavior of surface modifications for a dry deep drawing process

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Abstract

The global trend towards more environment-friendly and sustainable production motivates the development of efficient manufacturing processes. Forming technology has great potential regarding that due to its high material efficiency. Research is necessary to improve the sustainability of established forming processes such as deep drawing. One possibility to improve the environmental friendliness of deep drawing is the realization of lubricant-free processes. This avoids the usage of harmful lubricants. Additionally, it has the potential to shorten process chains by eliminating cleaning steps. However, dry deep drawing is associated with challenges. Due to the lack of a lubricant between tool and workpiece, friction and wear increase. An approach to overcome these challenges is the usage of modified tool surfaces. In this context, the aim of this research is to investigate dry deep drawing operations under application-oriented conditions. Firstly, the cause-effect relationships between the properties and tribological performance for a-C:H and ta-C coating systems as well as laserbased micro-textures are investigated in strip drawing tests using the workpiece materials DC04 and AA5182. Therefore, different amorphous carbon coating approaches for DC04 and AA5182 are evaluated. Beside of coatings, diverse laser micro-texturings are investigated and applied on forming tools. Key parameters are identified, which result in low friction and adhesion. Based on these findings, the different modifications are evaluated. Promising modifications are selected and applied in a novel test rig under application-oriented conditions to analyze their durability. The test rig enables the time- and material-efficient forming of a great number of parts. In this regard, in addition to the occurring process forces, the tool and component topographies are determined at periodic intervals in order to derive the cause-effect relationships between friction, wear and component quality as well as to demonstrate the feasibility of dry deep drawing operations under application-oriented forming conditions.

Keywords: Dry Deep Drawing, Tribology, Carbon Based Coatings, Laser Based Modification

1 Introduction and methodology

Dry deep drawing processes are motivated by their ecological and economic potential based on the disuse of environmentally harmful lubricants and the omission of the process step of component cleaning [1]. This absence of lubricants leads to challenges. Friction and tool wear in the form of adhesion increase due to the missing lubricant film between tool and workpiece. In this context, previous research has shown the potential of surface modifications for friction and wear reduction in dry deep drawing processes [2].

Based on those findings, the aim of this research is to investigate the durability of these measures, as shown in fig. 1. As a first step, the effects of coatings and laser textures will be investigated in laboratory tests in order to evaluate the measures. Amorphous carbon coatings are considered as one of the solutions to reduce friction and adhesive wear. Due to the unique bonding structures of carbon atoms, three types of carbon coating systems are considered: the extreme hard ta-C coating with a high percentage of sp^3 bonds, the hard a-C:H coatings with low production costs and its doped variation a-C:H:X. Additionally, ta-C coated surfaces are micro-textured by two different approaches. These micro-textures are

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characterized regarding their tribological behavior in strip drawing tests. The potential surface modifications with low friction of coefficient in strip drawing tests will be selected and applied on the real forming tools. We analyze the tribological behavior under application-oriented conditions to evaluate their wear durability. Non-modified tool surfaces serve as a reference for comparing the results. A novel wear test rig has to be developed for the material- and time-efficient characterization of the tribological behavior. This is implemented by a follow-on composite tool on a high-speed press and enables the production of 100 deep-drawn parts per minute with the sheet metal materials DC04 and AA5182. By measuring the tool and workpiece topography and the occurring process forces, the application behavior of the modifications and their durability can be evaluated as well as cause-effect relationships between friction, wear and component quality are derived. In addition, the results of the wear tests verify that by using specially designed modifications, dry deep drawing processes for a high number of forming operations are viable.

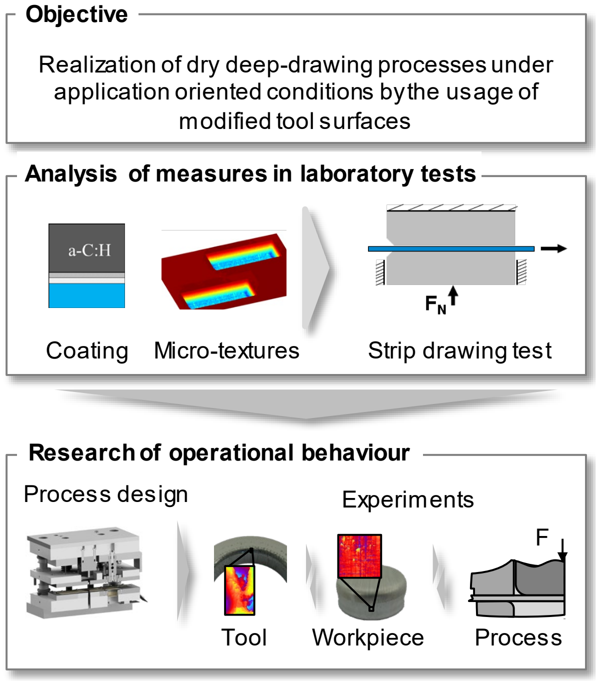

Fig. 1: Objective and methodology

2 Materials and investigated surface modifications

2.1 Materials

For the experiments conducted in this study, tools made of 1.2379 (X155CrVMo12) with a hardness of 60 HRC are utilized. Before modification, all tools are polished to a reduced peak height R_{pk} of 0.05 ± 0.02 µm, suitable for coating. As sheet material, the mild deep drawing steel DC04 and the aluminum alloy AA5182 with a sheet thickness of 1 mm each are chosen. The mechanical properties of both materials are discussed in [3]. The usage of DC04 is established for complicated component geometries [4], whereas AA5182 is used, for example, for car body parts [5]. Both workpiece materials have an EDT surface with an average roughness R_z of 5.14 ± 0.72 µm or 4.17 ± 0.39 µm respectively, fig. 2. The DC04 deep drawing steel is additionally zinc-coated for the corrosion protection. Prior to all the tests, the sheet metal is chemically cleaned and is dry according to [1].

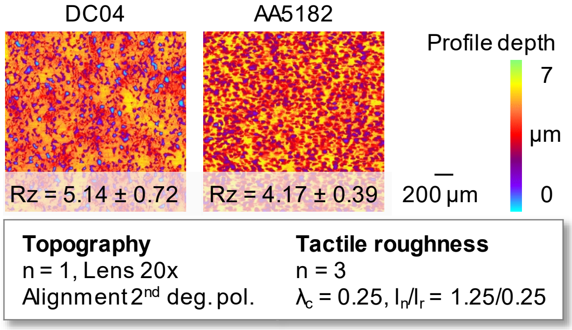

Fig. 2: Sheet metal topography

2.2 Surface modifications

As mentioned previously, tool-sided surface modifications is one of the potential solutions to prevent metallic transfer and prolong the service life of tools. In order to adjust the tribological conditions with low adhesion tendency and friction on the forming tools, diverse surface modifications are investigated. Their tribological behavior is evaluated in the strip-drawing tests against aluminum and steel sheets under dry sliding conditions. The tribometer setup and test conditions are summarized in [6]. One of the surface modifications are carbon-based PVD/PECVD coating systems. Due to the unique chemical structures and atomic bonds carbon-based coatings are well known for their beneficial and adjustable properties in the fields of mechanical [7] and tribological [8, 9] applications. In addition, laser-based micro-textures are considered as a second solution to control the tribological conditions. Moreover, they can be used to change surface properties. For example, it was demonstrated, that laser based micro-textures can create strongly hydrophilic or hydrophobic surfaces [10].

In the next step, these surface modifications will be analyzed concerning their production, characteristics and tribological behavior in details.

2.2.1 Amorphous carbon coatings

To realize the dry deep drawing process, amorphous carbon coatings are considered as one of the potential solutions. The carbon atoms can exist in diverse physical states due to different electronic arrangements, which results in solids with different properties like diamond, graphite, graphene and amorphous carbons. Under them, the amorphous carbon is widely used as coating on mould building, forming tools and machine elements, because of simple production techniques and low costs. The amorphous carbon coatings are coating variations, which have a mixture of sp^2- and sp^3-hybridized carbon atoms. Depending on the ratio of sp^2- and sp^3-bonds, their properties like the hardness, coefficient of friction and other properties can be adjusted over a wide range. In addition, the carbon matrix can be doped with metal (in this case tungsten, titanium) or non-metal elements (in this case silicon, nitrogen and oxygen) to archive special requirements. Within this project, various amorphous carbon coatings were investigated and deposited on the forming tools. The coated tools are evaluated concerning their tribological behavior under dry sliding conditions. Previous work [11] shows, that the dominated wear mechanisms during dry deep drawing is metallic transfer from the sheet material to tool surface. Thus, the applied coatings on tool surfaces are expected to have anti-adhesion effect. For the low coefficient of friction, high sp^3- but low sp^2-carbon bonds ratio in a-C:H are desired, because the sp^2-bonded carbon leads general to higher adhesion tendency[12]. After coating deposition, the coatings will be after-treated with soft polishing cloth. The aim of this step is to remove the roughness peaks, which results from the coating's growth and its columnar structures [13]. Investigation [6] about the relationship between the reduced peak height R_{pk} and the coefficient of friction showed, that a lower R_{pk} value led to a lower friction, especially during sliding against aluminum alloys. If the hard amorphous carbon tips interlock into the ductile and textured aluminum sheet, the risk of initial metal transfer rises and the service life of tools is shortened. Besides the above mentioned three factors: a lower roughness peak height by polishing, an anti-adhesion effect and low ratio of sp^2-bonds, other factors, like mechanical properties with hardness-to-elasticity ratio and an further reduced sp^2-bonds ratio by changing the deposition techniques, are investigated and evaluated in the tribological tests. The results in tribological tests help to identify the key factors regarding PVD and PACVD coatings, which contributes to lower coefficient of friction and long service life.

Investigated amorphous carbon coatings and their basic properties are summarized in table 1. Characterization methods and implementation parameters for coating thickness, hardness and adhesion to substrate are mentioned in previous works according to VDI 2840 [14].

Tab. 1: Compared Investigated coating systems with comparison with other coatings from previous works

Item	Coating thickness t in µm	Hardness H_{IT} in GPa	Indentation modulus E_{IT} in GPa	HF class
ta-C [15]	1.33 ± 0.03	54.6 ± 7.1	330.6 ± 52.4	HF 2
a-C:H:W [16]	2.35 ± 0.05	6.9 ± 1.6	86.1 ± 7.5	HF 1
a-C:H [16],(standard)	1.8 ± 0.1	17.5 ± 1.0	137.9 ± 5.7	HF 3.5
a-C:H (sp-Cr interlayer) [19]	2.6 ± 0.1	17.0 ± 0.7	131.6 ± 5.0	HF 3.5
a-C:H (sp-graphite)	0.63 ± 0.04	24.1 ± 3.3	194.8 ± 18.6	HF 3
a-C:H/ a-C:H:SiO/ a-C:H	2.77 ± 0.02	20.3 ± 2.6	151.8 ± 17.5	HF 3

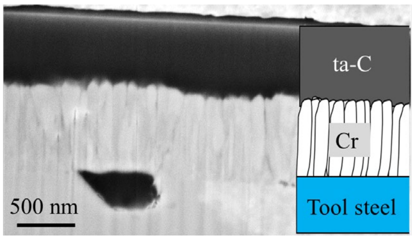

Fig. 3: Coating architecture of tetrahedral amorphous carbon (ta-C)

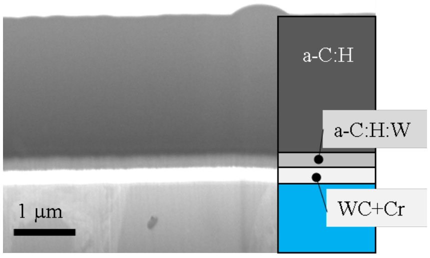

Fig. 4: Coating architecture of hydrogenated amorphous carbon (a-C:H)

The investigated ta-C coating system was produced by pulsed laser ablation through an industrial partner. To enhance the coating adhesion to substrate a chromium adhesive layer was deposited, as it is shown in Fig. 3. The applied standard and modified a-C:H coating systems have a uniform coating architecture. For a high adhesion to steel substrate, chromium Cr adhesive layer, tungsten carbide WC interlayer and a-C:H:W gradient layer were deposited prior to a-C:H functional layer according to DIN 4855 [17]. The mechanical processing and cleaning procedures of substrate and the deposition process of Cr/WC/a-C:H:W-layers prior to functional layer were already documented in previous work [3]. The a-C:H:W coating system has the same architecture and adhesive layer as the a-C:H coatings. The a-C:H:W layer is just thicker deposited than that in Fig. 4. Deposition parameters are reported in [18]. The a-C:H (sp) implies a modified coating system by depositing chromium adhesive layer through magnetron sputtering, while the adhesive layer in the standard system was vacuum arced [19]. Sputtering the chromium adhesive layer leads to much lower roughness than that by vacuum arcing due to droplets formation [20], so that the after-polishing of coating surface can be saved or shortened. The a-C:H (graphite) was produced by magnetron sputtering of a graphite target, in order to vary the sp^2- and sp^3-bonds in an expanded range than that of the standard a-C:H by PECVD. The graphite target was sputtered by 1.0 kW using a pulsed power supply at 70 kHz and a holing time of 4 µs. The sputtering gas was argon with small amount of acetylene, which have flow rates of 200 sccm and 20 sccm, respectively. The applied negative substrate bias voltage was 200 V. Besides the standard a-C:H functional layer, its multilayer variation was parallel investigated. The aim for this was to change its mechanical properties with various hardness-to-elasticity ratio without changing the top layer. The multilayer design was done with three monolayers with the sequence of a-C:H/a-C:H:SiO/a-C:H. The total coating thickness was attempted to keep the same as the functional layer in the standard system. The intermediate layer a-C:H:SiO was deposited by adding 10 sccm hexamethyldisiloxane (HMDSO) in the acetylene-argon-atmosphere with each 220 sccm and 40 sccm, respectively.

2.2.2 Laser based micro-textured coatings

In an additional step, we micro-texture the coating systems to evaluate the influences on the tribological system. Therefore, two different texturing approaches of ta-C coatings are compared. To reduce the heat input and prevent graphitization, both techniques use ultra-fast lasers. For removing the ta-C coating locally, a wavelength of 1064 nm is used. Since the ta-C is highly transparent for this wavelength, the absorption takes place in the underlying Cr layer. As a consequence, the Cr-layer is locally heated and expands rapidly, leading to a local ablation of the ta-C layer. Since, the coating is not vaporized the process is highly energy-efficient [21]. However, this technique only supports the local ablation of the complete layer thickness. This results in a metallic structure bottom. An alternative technique, which can compensate for this restriction, uses an ultra-fast laser operation at a wavelength of 355 nm. In contrast to the previous approach this wavelength is absorbed linearly by the ta-C coating. This enables accurate texturing with texture depths lower than the coating thickness [21]. For both techniques the samples were cleaned in an ultrasonic isopropanol bath to remove possible melt droplets originating from the ablation process. In the following, these surface modifications are investigated regarding their tribological behavior.

3 Investigation on measures in laboratory tests

The above-mentioned surface modifications are evaluated in strip-drawing test under dry sliding conditions. This test enables the first observations of friction and adhesive wear with a simple test rig, which helps to select suitable surface modifications for the sequent tests on forming tools. Two industrial common used sheet materials, galvanized steel DC04 and aluminum alloy AA5182, were applied in this test. Further experiment conditions are documented in [21].

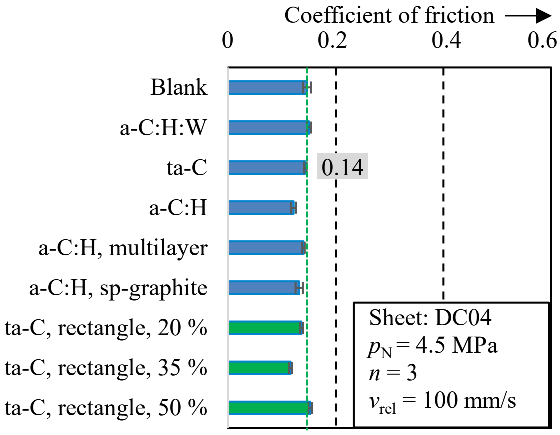

Fig. 5: Coefficient of friction in strip drawing test against steel sheet DC04 under dry sliding condition

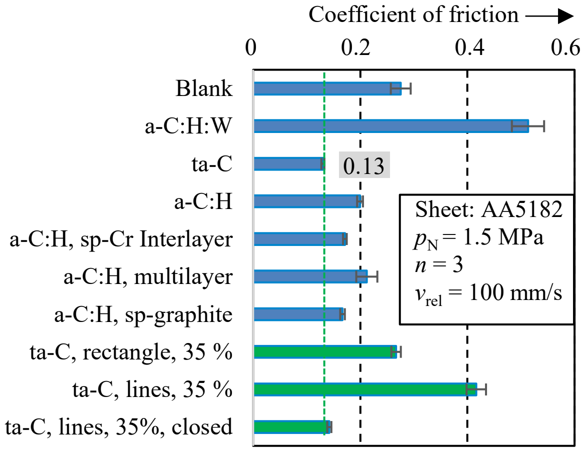

Fig. 6: Coefficient of friction in strip drawing test against aluminum alloy AA5182 under dry sliding condition

Fig. 5 shows that the coefficients of friction against steel sheet DC04 are generally low, independent on the surface modifications. The reason is the corrosion protective zinc film on the DC04 sheet surface, which led to low friction. Laser-based mirco-textures enable to adapt the friction from 80 % to 110 %. Here the friction is affected by the degree of coverage [21].

The friction against aluminum alloy depends strongly on the surface modifications. The a-C:H:W coating shows 300 % higher friction in the dry contact of aluminum alloy than that of the ta-C coating. The a-C:H:W coating has a columnar structure from growth process, which leads to an inhomogeneous and cauliflower-like surface topography. Even after polishing, the ductile aluminum alloy is sheared through the edge of micro-textures and the initial adhesion storage in the valley on the surface. In addition, the element tungsten leads to high adhesion tendency in direct contact with aluminum, [22] thus, the aluminium tends to stick on the tungsten doped amorphous carbon coated surface. The a-C:H and ta-C coated friction jaws show 30 % and 50% lower friction against aluminum alloys than that of uncoated steel, respectively. The lower friction can be explained in two aspects. First, they have certain percentage of sp^3 hybridized carbon bonds. Even the a-C:H coatings, which are deposited from acetylene-argon gas mixture, have 20 %-40 % percentage of sp^3 bonds [23], which prevents the adhesion and benefits the friction. However, no linear relationship between the percentage of sp^3 bonds and friction was found: the a-C:H coating with lower sp^3 ratio shows similar low friction as the ta-C coating. The second important reason is the low R_{pk} value, which reduces the risk of the formation of initial aluminum adhesion. Since the a-C:H coating shows anti-adhesion effect, further modifications concerning the coating design were conducted. The modifications were also tested in strip drawing test. The results are summarized in fig. 5 for DC04 and fig. 6 for AA5182. The modified a-C:H coating system by sputtering chromium adhesive layer with homogeneous surface in as-deposited state shows a little lower friction than that of the standard a-C:H system. However, the mechanical polishing cannot be saved, otherwise the resulted friction is two times higher than that of the treated surfaces. It can be seen, that the a-C:H coating system with sputtered a-C:H functional layer has a little lower friction than that of the standard coating system. The multilayer design has however higher friction.

In contrast to DC04, laser based micro-textures do not allow to reduce the friction in strip drawing tests with AA5182. Textures with a metallic structure bottom show an increase of friction up to 220 %. This is caused by the strong adhesion tendency of aluminum. Even micro-textures with a closed ta-C layer show a slightly increased friction in contrast to an unstructured tool surface against AA5182 [21].

The worn surface was analyzed with confocal microscopy. From fig. 7 it could be seen, that metallic transfer was found on the steel and a-C:H:W test jaws. On the a-C:H and ta-C surfaces there are no obvious adhesion. Although, the friction can be reduced, adhesion is an important problem as can be seen in fig. 8. Here a laser scanning microscope image of an exemplary jaw is shown before and after a strip drawing test in contact with DC04. After the tests, adhesion of zinc occurs mainly in the region of the structure rims. Therefore, those micro-textures cannot be used in an industrial application of dry deep drawing. As a consequence, the micro-textures are not evaluated in further experiments.

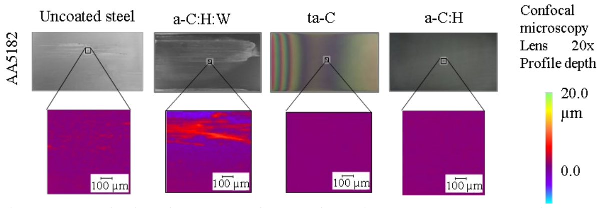

Fig. 7: Analysis of worn surfaces of steel, a-C:H:W, ta-C and a-C:H coatings.

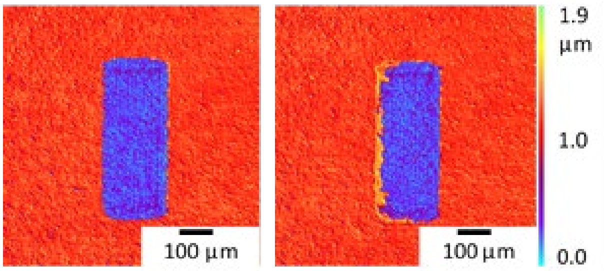

Fig. 8: Micro-textured friction jaw, bevor (left) and after (right) strip drawing test against DC04 under dry sliding condition

The simple laboratory tests show that the dominated wear mechanism between tool steel and aluminum alloy is metal transfer. To realize the dry metal forming, adhesion from sheet material to tool surface should be avoid. The ta-C show low friction and the tested surface shows no adhesion or other material rest. Besides the ta-C coating, the a-C:H coating system shows similar low friction as that of ta-C coating. Compared to the ta-C coatings, the a-C:H coatings deposited in acetylene-argon atmosphere is easy to produce concerning low machine investment and production costs, which makes its application on tool surface attractive. Therefore, the a-C:H and the ta-C coatings are selected for durability tests.

4 Research of operational behavior of measures

4.1 Development of a new test rig

In the laboratory test it was proven, that a-C:H and ta-C coatings reduce the friction as well as wear. The laboratory test only investigated the tribological behavior of the measures for a low number of forming operation. One requirement of deep drawing tools is a high quantity. Therefore, the durability of the modifications has to be investigated under application-oriented conditions for a high number of forming operations. The drawing of rectangular cups, which has been used to evaluate the surface modifications in [3], is not suitable for this purpose, as this setup is not capable to produce a high number of parts with a justifiable amount of effort. This motivates the development of a novel experimental setup. A primary requirement of the novel setup is that it should enable dry deep drawing operations. This ensures characteristic tribological loads of dry deep drawing processes. Another key requirement is the material- and time-efficient production of a high number of components, which results in a high demand for automation regarding material feed, component handling and forming. A further requirement for the test rig is that the topography of the used tools as well as the produced parts can be analyzed in a non-destructive way.

The requirements imply the deep drawing in a follow-on composite tool. The advantage of this kind of tool is that, due to simple component handling, short cycle times and high quantities can be achieved [24]. The usage of follow-on composite tools requires the supply of semi-finished products from the coil. For the dry deep drawing in this research, a follow-on composite tool with four stages is used. The stripe pattern and stages, as well as the tool system are shown in fig. 9.

In the first stage of the forming process, both edges of the coil are perforated. The perforations are used in combination with locating pins in order to position the coil in the subsequent forming stages. In the second forming stage, a blank with a diameter of 62 mm is stamped out of the coil using a double T-punch. The diameter of the blank was selected following [25] for a coil width of 90 mm. To transport the blank to the next forming stage, it is connected to the coil by strips with a width of 3 mm. In the third forming stage, the blank is deep drawn. This process consists of four steps. For the first step, the strips connecting the blank to the coil are sheared off by the edge of the blank holder. This prevents material flow from being influenced by the connection of the blank to the coil. In the second step, the blank holder applies a force specific to the workpiece material using pneumatic springs. The blank holder ensures crease-free deep drawing. A pressure of 4.5 MPa is applied to the DC04 parts, whereas a pressure of 1.5 MPa is used for the AA5182 sheets according to [2]. The black holder pressure was set in [2] to achieve winkle free parts. The punch then contacts the sheet metal and draws the entire blank through the die to produce a flangeless cup. By doing that, the highest possible sliding paths between tool and workpiece and thus high tribological loads are ensured. During the entire deep drawing process a piezoelectric sensor measures the forming force of the punch. Once the bottom dead center has been reached, the cup is demoulded by spring-loaded scrapers in combination with the backward movement of the punch, and ejected downwards. In the last stage of the process, the remaining parts of the coils are separated. The process restarts with the subsequent feed of the coil.

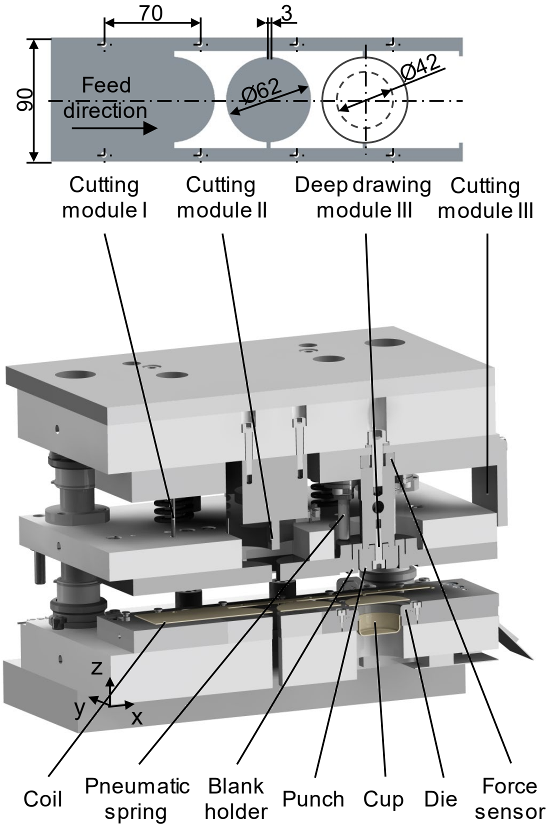

Fig. 9: Stripe pattern and tool system

The geometry of the tool parts shown in fig. 10 is based on the blank diameter of 62 mm and sheet thickness of 1 mm. A punch diameter of 40 mm and a drawing gap of 1.4 mm are selected based on [25], which results in a die diameter of 42.8 mm. According to [26], a die radius of 3 mm is selected based on the blank diameter, the punch diameter and the sheet thickness. The punch radius is set to 4 mm.

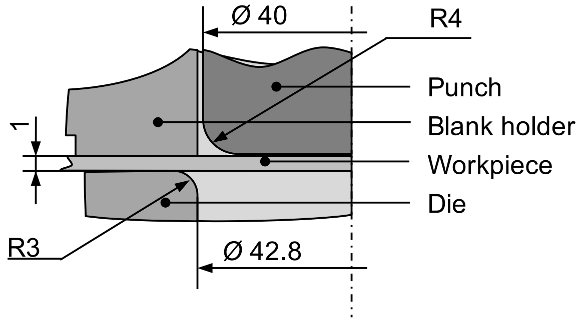

Fig. 10: Tool geometry

For the realization of an automated forming process, peripherals are required. Fig. 11 provides an overview of these elements.

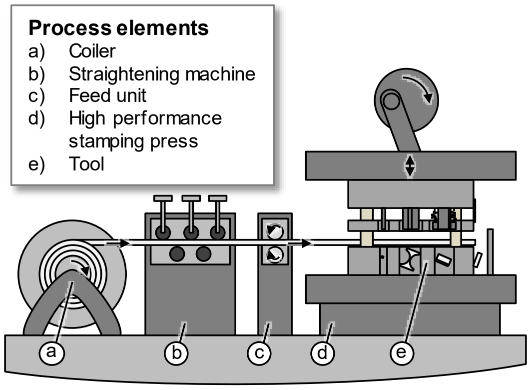

Fig. 11: Process elements

The peripheral consists of a coiler for the automated supply of the cleaned sheet metal. After having been in the coiler, the sheet passes through a straightening machine in order to remove deformation caused by the windings. The coil is then supplied to the tool system by the feed unit at a rate of 70 mm per press stroke. The follow-on composite tool is operated on a high-speed press type BASTA 510 from Bruderer AG. The forming of the cups is performed by moving the press ram with 100 strokes per min. The tool system thus enables the dry forming of 100 cups per minute and is used to investigate the tribological behavior of tailored deep drawing tools.

4.2 Tribological behavior of measure for dry deep drawing under application-oriented conditions

For the investigation of the tribological behavior of surface modifications for the realization of dry deep drawing operations, the change of tool topography due to wear is of particular interest. A further objective is the analysis of the component topography. This enables the evaluation of the effects of tool wear on component quality. The maximum process force will also be analyzed. By determining the relationship between tool wear, component quality and process force, the suitability of the process force for in-situ process monitoring will be evaluated. The tool and component topography are characterized in fine intervals up to 1,000 forming operations and then analyzed every 1,000 strokes. For each measure and sheet material, 3,000 cups are formed. With the uncoated tools, components were produced until the quality of the parts was no longer sufficient.. This applies when three fractured parts occur or if the roughness of the parts rises above an average roughness depth R_z of 15 µm. With DC04, the cups show a roughness over 15 µm after 200 forming operations. When using AA5182, the components crack after ten strokes, which is why the tests for uncoated tools are stopped at this point.

The analysis of the drawing die topography after the forming operations shown in fig. 12 indicates that the tools show a wear behavior specific to both modification and workpiece material. After 200 forming operations of DC04 and ten strokes with blanks out of AA5182 for the uncoated tools, significant wear occurred in the radii of the dies. The blank is redirected at the drawing die radius. Thus, this is the highest loaded area [27], which means wear occurs locally. For the a-C:H coated tools there are no signs of wear after 3,000 forming operations of DC04.

When forming AA5182 on the contrary, the die exhibits wear. However, the size and shape of the worn area are clearly smaller than with uncoated tools. With the ta-C coated tools, there are no visible signs of wear after 3,000 forming operations with both DC04 and AA5182.

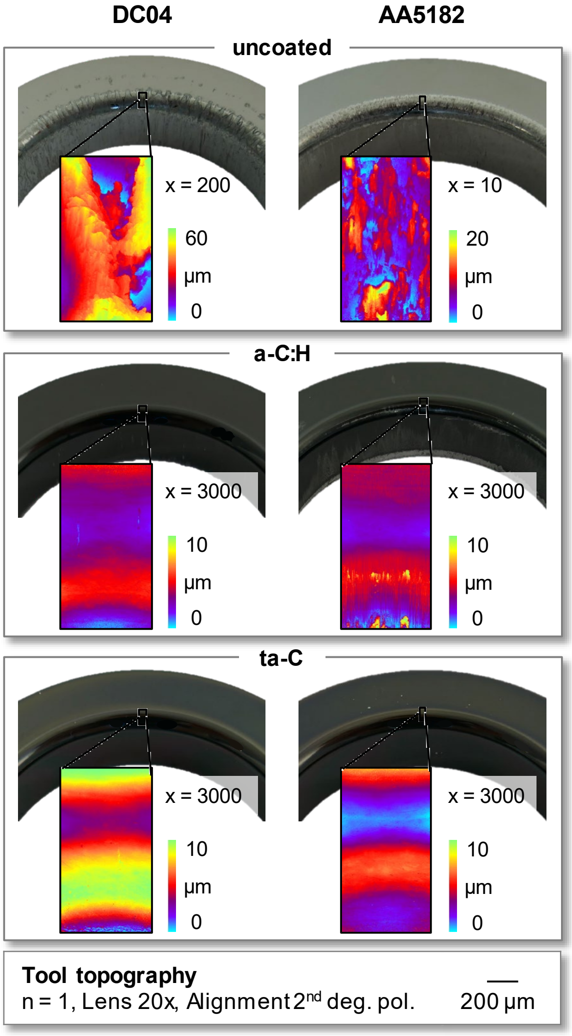

Fig. 12: Tool topography

For the analysis of the dominant wear mechanism, the tools at which topography changes occur are examined with an energy-dispersive X-ray spectroscopy (EDX), fig. 13. The EDX analysis enables the identification of the elementary composition of the tool surfaces based on the characteristic radiation spectrum of the elements. For the uncoated drawing die with which DC04 was formed, the tool topography consists mainly of zinc. Thus, it can be assumed that the change in tool topography is caused by the adhesion of the zinc coating of the DC04 sheet metal to the tool surface. For dies with which AA5182 was processed, the worn tool surface consists partly of aluminum. Consequently, during the forming of AA5182, a material transfer from the sheet material to the tool surface occurs. As the analysis of the tool topography has already shown, fig. 12, there are less aluminum adhesions on tools coated with a-C:H. The EDX analysis thus confirms that adhesion is the dominant wear mechanism for both DC04 and AA5182 during dry deep drawing under application-oriented conditions.

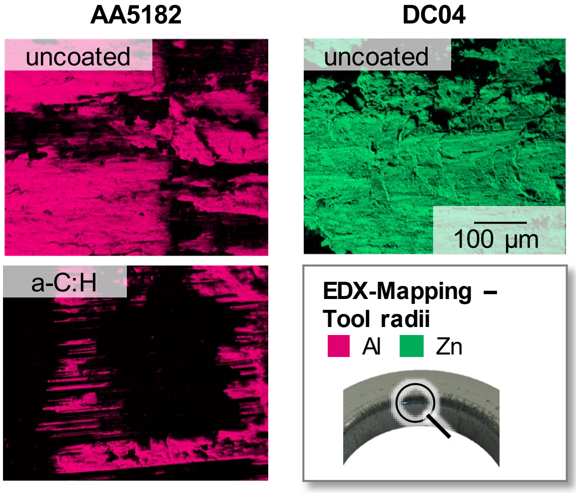

Fig 13: EDX-analysis of tool surfaces

For the quantitative analysis of tool wear, the reduced peak height R_{pk} is determined in fig. 14. In [2] the applicability of the R_{pk} value for describing the tribological behavior of dry deep drawing tools was shown. The roughness is determined at the radius of the drawing die as the most critical area for wear [27], fig. 12. For the uncoated tools, the roughness increases after five forming operations from a reduced peak height R_{pk} of 0.05 ± 0.02 µm to 2.29 ± 1.35 µm when forming DC04 and 2.53 ± 1.07 µm for AA5182 blanks. Afterwards, there is no change in roughness for the uncoated tools forming DC04 and AA5182 until the end of the experiments. A similar behavior for dry metal sliding contact is shown in [28]. Thus, it can be assumed that a stable level of wear has been achieved after the first forming operations.

When forming DC04 cups with a-C:H coated tools, the reduced peak height R_{pk} decreases from an initial roughness of 0.16 ± 0.03 µm. After 3,000 formed parts, the tool has a roughness of 0.09 ± 0.03 µm. During the forming of AA5182, on the other hand, the roughness at the radius of the drawing die increases significantly to 0.48 ± 0.31 µm. The roughness values confirm the optical analysis of the tools (fig. 12), in which wear was recognizable after forming AA5182 with a-C:H coated tools. The increase in standard deviation is due to the irregular structure of the worn topography. In comparison with the uncoated tools, the a-C:H coating significantly improves wear resistance by completely preventing wear for the workpiece material DC04 and greatly reducing wear for blanks of AA5182 because of a reduced adhesion tendency.

The change in roughness for the ta-C coated tools is similar for the forming of DC04 and AA5182. For both materials, forming causes a slight decrease in roughness, as it already occurred for the tools coated with a-C:H during the forming of DC04. It can be assumed that the surface caused by the coating process [29] is smoothed in by the forming process. The comparison of the uncoated and ta-C coated tools reveals that the coating completely prevents wear for both sheet metal materials up to 3,000 forming operations, whereas uncoated tools already wear strongly after five strokes. The ta-C coatings thus significantly improve the tribological performance of the tools by preventing wear. In comparison of ta-C to a-C:H coatings, there is no difference when forming DC04. With the workpiece material AA5182 on the other hand, ta-C prevents wear more effectively. It can be assumed that the lower wear resistance of a-C:H is caused by its higher amount of sp^2, which tends to adhesion [15].

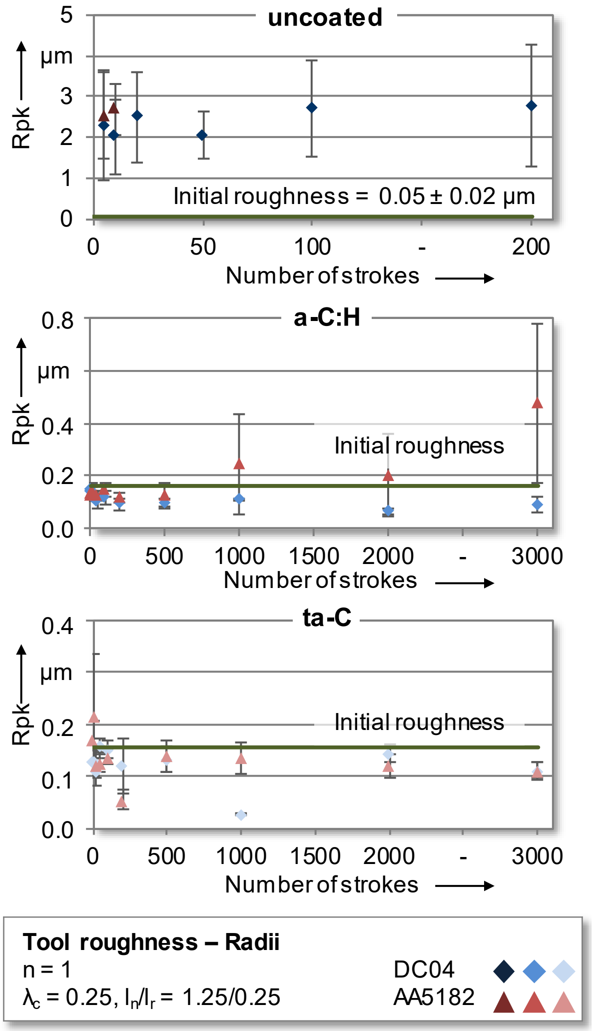

Fig. 14: Roughness of the die

The topography of the workpiece is particularly important for sheet metal parts, as it influences for example their ability to be painted [30]. The condition of the tool surface determines the component topography. Consequently, the topographies of the deep-drawn cups are analyzed to determine the relationship between tool wear and component quality. Fig. 15 shows the topographies of the last produced cups for each tool system.

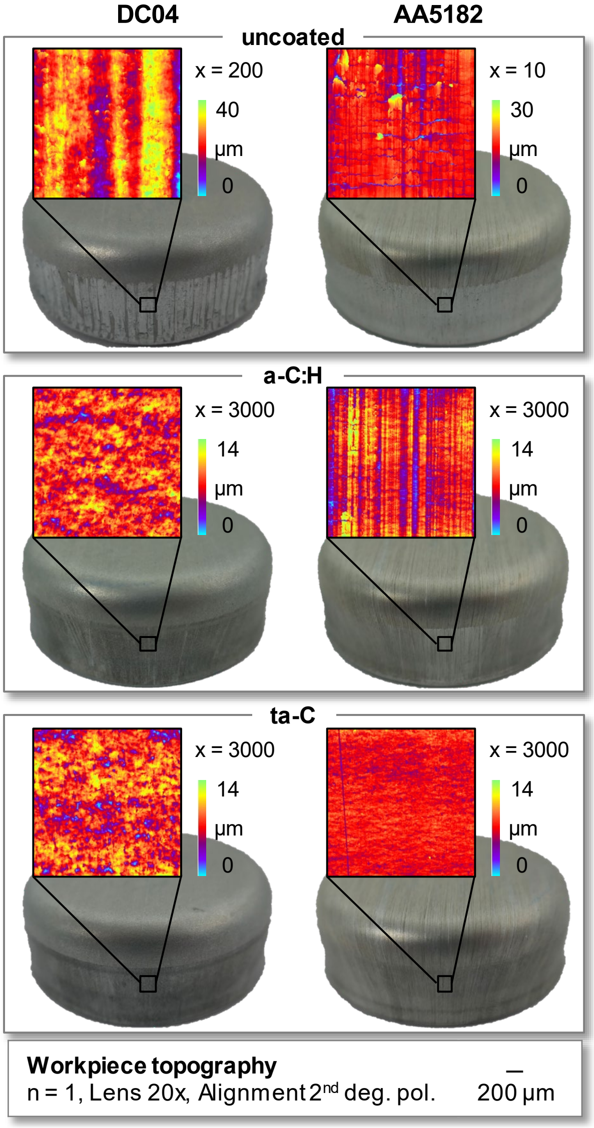

Fig. 15: Topography of the cups

For all cups, a change of topography in the area of the frame occurs in comparison to the initial surface of the sheet metal shown in fig. 2. For cups formed with uncoated tools, the roughness increases strongly. This is due to the increase in tool roughness due to wear, fig. 14. The adhesion sticking to the tool grooves through the workpiece surface, causing a rough topography with visible scratches parallel to the drawing direction. On DC04-cups formed with coated tools no grooves are visible on the frames due to the fact that both the a-C:H and the ta-C coating completely prevented wear during the forming of DC04. The cups made of AA5182 which were formed with ta-C coated tools also show no grooves. For the AA5182 cups which were processed with a-C:H coated tools, grooves are visible after 3,000 strokes due to tool wear.

In order to quantitatively analyze the influence of the tool wear on the component surface quality, the mean roughness R_z is measured tangentially to the cup frames, shown in fig. 16, as the mean roughness R_z is an established parameter for evaluating the surface quality of sheet metal components. For all cups made of DC04, the mean roughness R_z increases from an initial roughness of 5.14 ± 0.72 µm. In contrast, the roughness of AA5182 cups only increases above the initial roughness of 4.30 ± 0.40 µm for cups formed with uncoated tools. For cups formed with coated tools, no influence of the coating system or the number of cups already formed is detectable for DC04 and AA5182. Consequently the grooves of the AA5182 cups formed with a-C:H coated tools (fig. 15) are too small to increase the initial roughness of the sheet metal. The roughness of DC04 cups manufactured with uncoated tools increases to 15.80 ± 3.04 µm after 200 forming operations. This is caused by an increasing wear of the drawing die after the radius run-out, fig 14. The cups made of AA5182 which were manufactured with uncoated tools have a component roughness of 13.00 ± 4.49 µm after only ten forming operations. The analysis of the workpiece surfaces shows that both coating systems investigated improve the workpiece quality in terms of roughness and prevent high roughness due to tool wear. Both coating systems thereby enable dry production of deep drawn components.

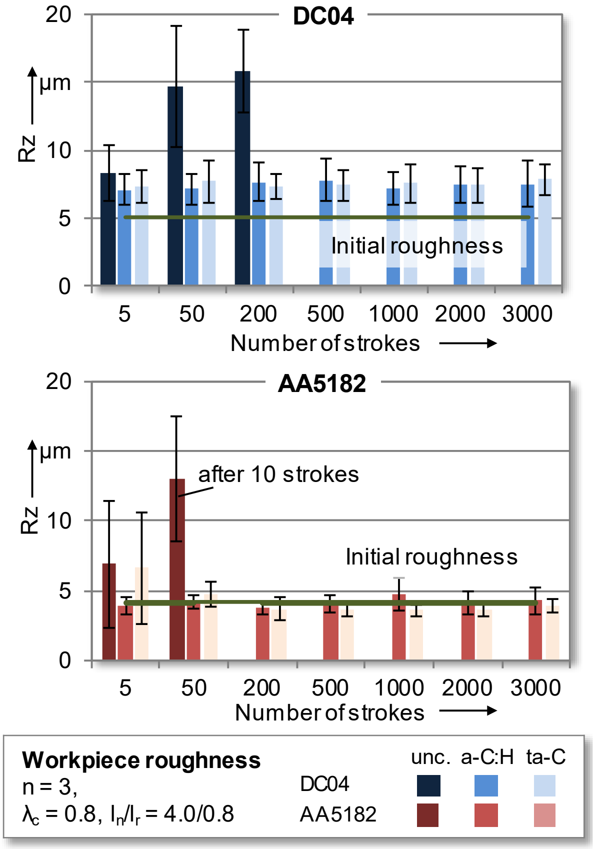

Fig. 16: Roughness of the cups

When analyzing a forming process, the maximum forming force is of importance, since this parameter is necessary for the selection of an appropriate forming machine [31]. In addition, the analysis of the maximum forming force evaluates its potential for an in-situ monitoring of the tool condition without extensive analysis of the tool or workpiece topography and provides information about the friction.

As a first step, the mean maximum forming forces of the first five forming operations for each tool are examined, shown in fig. 17. The highest maximum forming force of 31.8 ± 0.7 kN is required for forming of DC04 with uncoated tools. The usage of tools coated with a-C:H or ta-C reduces the forming force to 28.7 ± 0.3 kN and 27.5 ± 0.4 kN. The decrease of the force is due to the reduction in friction caused by the coatings shown in [2]. A similar behavior occurs with the forming of AA5182. Here, the maximum forming force is reduced from 27.8 ± 0.6 kN to 19.4 ± 0.6 kN and 19.8 ± 0.3 kN by using an a-C:H and a ta-C coating respectively. The overall lower forming force required for cups made of AA5182 compared to DC04 is a result of the lower strength of AA5182 [3].

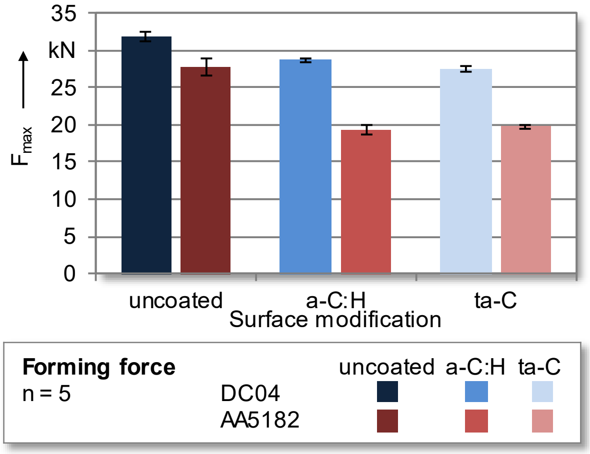

Fig. 17: Maximal forming forces for the first five strokes

In addition to the first five strokes, the change in forming force over the remaining forming operations, shown in fig. 18, is of interest for evaluating the tribological behavior of the tools. For the forming of DC04 with uncoated tools, the required maximum forming force increases from 30.5 kN for the first cup to 33.9 kN for the 200th stroke. The rise in forming force is caused by higher friction due to continuous tool wear. When forming AA5182 with uncoated tools, the maximum forming force increases from 27.4 kN to 32.4 kN during ten forming operations. The change in forming force due to wear is more significant with AA5182 than with DC04, as AA5182 has a higher tendency of adhesion [2].

The usage of coated tools causes a reduction of maximum forming forces during the first 50 strokes at DC04 and during the first 500 strokes at AA5182. Reducing maximum forming forces is due to a decrease in friction caused by a reduction in tool roughness during the first strokes, shown in fig. 14. Subsequently, the maximum forming forces for the remaining DC04 cups remain on a constant level. This confirms the analysis of the tool topography, where no wear is detected for coated tools when forming DC04, fig. 12. When forming AA5182, a comparable behavior occurs for tools coated with ta-C. For tools coated with a-C:H on the other hand, the forming force increases slightly from 1,500 strokes, which is caused by an increase in friction due to adhesive wear, fig. 13.

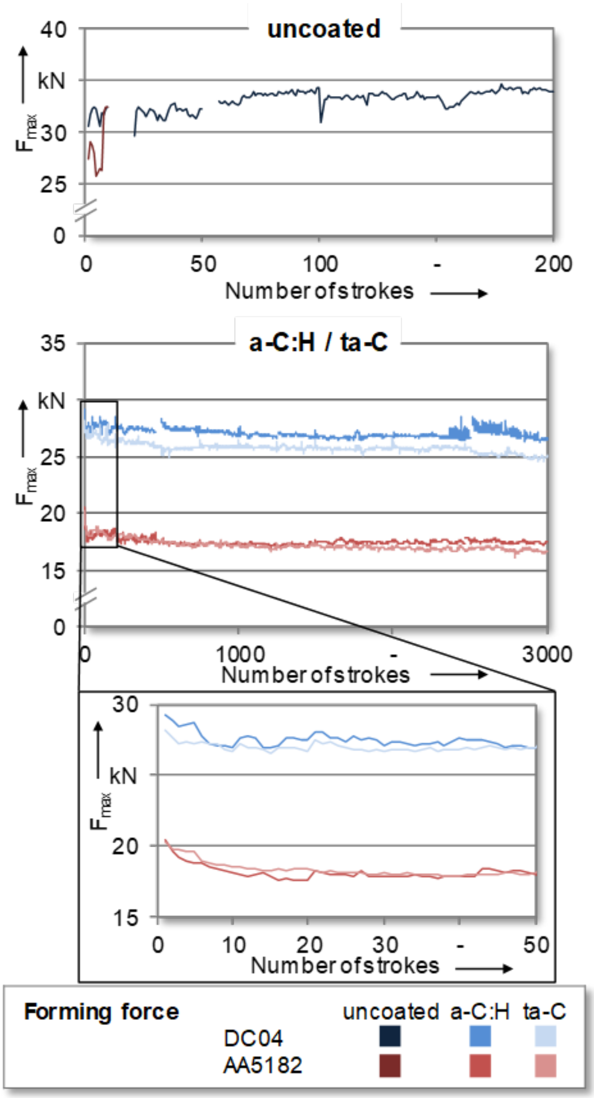

Fig. 18: Maximum forming forces

The combined evaluation of the parameters tool topography, component topography and maximum forming force enables the deduction of cause-effect relationships occurring during dry deep drawing operations. The greater adhesion tendency of the workpiece material because of the lack of lubricant leads to critical wear of uncoated tools, fig. 12. The higher tool roughness caused by wear results in rising friction, which is indicated by increasing process forces, fig. 18. The greater friction and tool roughness in turn reduce component quality. On the one hand, the risk of fractured components rises. For instance, when forming AA5182 with uncoated tools, three cracked components occur during the first ten strokes. On the other hand, both for DC04 and AA5182, the surface quality of the formed components decreases, fig. 16. Thus, dry deep drawing processes may not be realized with unmodified tools under application-oriented conditions. In contrast, the investigated coating systems enable dry deep drawing processes under application-oriented conditions by avoiding tool wear as a result of a lower tendency to adhesion. Consequently, the negative impacts of tool wear in terms of process force and component quality are avoided. Fig. 19 evaluates the investigated tool surfaces regarding their suitability for dry deep drawing processes under application-oriented conditions. It can be shown that unmodified dies are unsuitable for dry deep drawing, whereby the forming of AA5182 is particularly critical. The use of a-C:H or ta-C coatings, on the opposite, allows dry deep drawing. For the workpiece material DC04, there is no difference in suitability between a-C:H and ta-C, whereas ta-C is better suited for forming AA5182.

Material	DC04	AA5182
Tool surface		
uncoated	partly unsuitable	unsuitable
a-C:H	suitable	partly suitable
ta-C	suitable	suitable

Fig. 19: Evaluation on different tool surfaces

5 Conclusion and outlook

The potential of different modifications for the realization of dry deep drawing processes by overcoming the challenge of increasing friction and wear was analyzed using the sheet metals DC04 and AA5182. The laboratory test showed that the undoped amorphous carbon coatings have adhesion- and friction reducing effects, especially for aluminum alloys. For sheet steel, the coated tools can protect the surface to prevent adhesion wear, which prolonged the tool service life. After depositing the coatings on tool surfaces, it is essential to remove the roughness peaks, which come from coating growth. The present results show that the mechanical polishing is so far considered as the most effective method and ensures low friction in tribological use. For the additionally investigated laser-based micro-textures, it was found, that they can reduce the friction in contact with DC04. However, the formation of adhesive wear prohibits their usage in dry deep drawing in an industrial application. For AA5182 the strong adhesion tendency prevents a reduced friction and therefore a rational application of the micro-textures in dry deep drawing.

Based on the results of the laboratory tests, an a-C:H and a ta-C coating were selected and used in a newly developed test rig for the application-oriented investigation of the durability of the surface modifications. The results confirm that dry deep drawing processes with unmodified tools are not practicable for both DC04 and AA5182. Strong adhesive wear causes an increase in friction, verifiable by the higher process force. In addition, the component quality is not sufficient since cracking is enhanced by high friction and the component topography is negatively influenced by wear-induced high tool roughness.

Both ta-C and a-C:H coatings completely prevent wear due to the reduction of adhesion tendency for the material DC04 and thus enable dry production of 3,000 components. Apart from a short running-in phase in which the roughness of the coatings decreases slightly, the modifications show a stable behavior and enable the production of cups with constant quality. Considering the adhesion critical workpiece material AA5182, 3,000 cups can be manufactured without wear with a ta-C coating as well. The a-C:H coating shows first adhesive wear after 3,000 formings. However, the occurring wear is still too insignificant to negatively influence the component quality. It can be assumed that the lower wear resistance of the a-C:H coating compared to ta-C is caused by a higher adhesion-critical sp^2 content.

The results of the tests have proven the reliability of dry deep drawing processes by applying tailored tool surfaces for simple component geometries. In future investigations, the transferability of the results onto complicated component geometries should be examined. Accordingly, for the surface modifications, sustainability and further reduction of production costs will be the next focus. Further improvement of coating systems concerning adhesion to substrate, deposition rate and coating architecture has scientific meaning. Considering the material, some questions, like the function of hydrogen in amorphous carbon coatings on tribological application and other carbon coatings, can help to understand more and deeper about dry sliding process against metal, especial aluminum alloy.

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