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Experimental investigation of tool-sided surface modifications for dry deep drawing processes at the tool radii area

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Abstract

In conventional deep drawing processes lubricants are applied to reduce friction and wear. Demands for increased sustainability, environmental protection and resource efficiency motivate the realization of lubricant-free forming processes. The direct tool-workpiece contact during dry deep drawing leads to changed tribological conditions. Especially in the areas of increased normal and shear stresses, such as the die radius, the dry contact causes an increased risk of wear and damage to the sheet surface. A well-known approach to face the challenges of dry deep drawing of steel sheets and aluminum alloys is the application of amorphous carbon based coatings on the tool surfaces. Within this study the tribological behavior of conventional and modified tool surfaces at the critical radii area is investigated with a strip bending rotation test. In this test, the friction coefficient is determined based on the relative movement between a rotating test cylinder and a sheet-metal strip bent in a die. For the tribological tests the sheet materials AA6014, AA5182 and zinc coated DC04 are applied. The modification of the tool sided surface was achieved by applying ta-C and a-C:H coatings to the test cylinder. In addition to tests with coated surfaces, tests with uncoated tools are carried out for reference. By analyzing the resulting friction coefficients for the different sheet materials, the suitability of ta-C and a-C:H coatings for dry deep drawing processes is evaluated comparatively. In order to investigate cause-effect relations as well as wear mechanisms, the tool and workpiece surfaces are characterized before and after testing.

Keywords: Dry Deep Drawing, Tribology, Carbon Based Coatings

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1. Introduction

Deep drawing as the most important method of sheet metal forming is used in industry for a variety of applications. The automotive industry is the main market. In order to achieve an optimal deep drawing result and to minimize tool wear, lubricants are conventionally used for deep drawing. Lubricants are usually made from fossil raw materials, which may be harmful when getting in contact with humans and the environment [1]. The lubricant application as well as the cleaning and drying of the sheets for further processing require additional resources. Against the background of current trends such as sustainability, environmental protection and resource efficiency, the desire of realizing lubricant-free forming processes is increasing [2]. The direct tool-workpiece contact during deep drawing without lubricant creates new challenges in terms of process design. The dry conditions result in an increase of friction and wear, that leads to a lower workpiece quality and favors premature tool failure [3]. This affects in particular areas with high relative movements and contact normal and shear stresses, as they are present at the tool radii [4]. One approach to meet the increased dry deep drawing requirements is the application of coatings to the tool surfaces. By the application of coatings as separating layers between tool and workpiece, the tools are adapted to the changed tribological conditions. Especially carbon based coatings, such as ta-C and a-C:H, are proved to reduce friction and wear. In flat strip drawing tests the friction coefficient for AA5182 was reduced by approximately 50 % for a-C:H and ta-C coated tool surfaces in comparison to conventional tool surfaces under dry conditions [5]. In order to analyze the tribological behavior of tool-sided a-C:H and ta-C coatings at the critical tool radii strip bending rotation tests are performed for steel and aluminum alloys. Additional to the determination of the friction coefficient, the tool and sheet surfaces were analyzed before and after testing.

2. Experimental design and procedure

2.1. Materials and Coatings

As sheet materials the mild deep drawing zinc coated steel DC04 and the two aluminum alloys AA5182 and AA6014 were investigated. All sheets have a thickness of 1 mm. Prior to the tribological tests, basic lubrication and soil were removed from the blanks using an acetone bath. The cleanliness was proved by an infrared sensor. In order to reduce wear and friction, the tool surfaces are coated. The coatings were deposited on fine polished test cylinders out of the cold working steel 1.2379 (X155CrVMo12). The hardness of the tool material is 60 ± 1 HRC. Diamond-like carbon based coatings (DLC) are known for their low friction coefficients as well as high chemical resistance and hardness. Especially for deep drawing of aluminum alloys the tribologically effective properties of DLC coatings led to reduced friction coefficients and punch loads [6]. In general, a-C:H coatings have a higher adhesive strength than ta-C coatings, whereas the ta-C coatings have higher hardness values. The basic amorphous hydrogenous carbon coating system (a-C:H) consists of a chromium adhesive layer, a WC interlayer, a-C:H:W interlayer and the a-C:H functional layer. For deposition a hybrid PVD/PECVD coating machine with a threefold rotating charging rack was used. The a-C:H functional layer was deposited by PECVD using C_2H_2 as precursor gas at a temperature of 80°C. The C_2H_2/Ar ratio was set to 220/40, which equals a ratio of 5.5:1. The substrate bias voltage U_{bias} was 450 V. The thickness of the coating system after deposition was measured to 2.4 ± 0.1 µm according to DIN EN ISO 26423. According to DIN EN ISO 14577-1 the micro hardness and indentation modulus of coating samples are measured to 1905 ± 80 HV 0.001 and 150 ± 5 GPa, respectively. The tetrahedral hydrogen-free amorphous carbon coating system (ta-C) also consists of an adhesive layer of chromium and the ta-C functional layer. The ta-C functional layer was deposited by a laser arc process, which is initiated by a laser pulse on the graphite target [10]. The specified total coating thickness is 1.9 µm. A magnetic field is used to filter the macro particles from the arc process and to ensure a smooth surface. The micro hardness and indentation modulus of coating samples is 5017.9 ± 1164.0 HV 0.002 and 330.6 ± 52.4 GPa, respectively. All coating samples have an adhesion of better than HF4 according to [7]. This represents a sufficient adhesion with small cracks and delamination around the Rockwell indentation. After the coating deposition the tool surfaces are mechanically treated by polishing and brushing. The brushing was applied to reduce the roughness of the ta-C and a-C:H coatings [8] and to generate comparable roughness levels.

2.2. Test setup

In order to evaluate the tribological behavior of the different coating types in the critical radius areas, strip bending rotation tests are performed. Suitability of this new laboratory test for modelling the tribological loads at the tool radii area of deep drawing processes is shown in [5]. Especially under dry conditions, the results of flat strip drawing test were successfully transferred to the strip bending rotation test. The strip bending rotation test is based on the relative movement between a rotating test cylinder and a bent sheet metal strip. Fig. 1 shows the basic structure of the test setup.

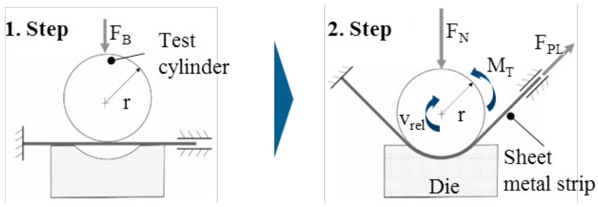

Fig. 1: Strip bending rotation test setup.

The sheet metal strip to be tested is positioned between the die and the test cylinder. The test cylinder with a radius r of 15 mm bends the sheet controlled by a bending force F_B into the die until the previously defined contact force F_N is reached. During the bending process, the clamping devices rotate to bend the sheet only in the area of the test cylinder. After reaching the contact pressure, the clamping device is locked in accordance with the defined wrap angle by dowel pins. It is possible to apply a preloading force F_{PL} to achieve a prestraining of the strip. In the present work, all tests are carried out without prestraining. By applying the contact force a homogeneously distributed surface pressure results in the contact zone between the test cylinder and the die. The relative movement between the cylinder and the sheet takes place in a second step by rotation of the test cylinder at the speed v_R. The rotation angle is measured during the experiment by means of a rotary encoder on the cylinder. A torsional moment sensor measures in parallel the torsional moment M_R, which is needed to rotate the test cylinder. In contrast to existing model experiments of the tool radii area, the new experimental design developed at the LFT [5] ensures a more even distribution of contact normal stresses. In addition, the Coulomb friction law frequently used in sheet metal forming is applied to calculate the friction coefficient μ by $M_T/(F_N{\cdot}r)$.

2.3. Experimental design

In order to investigate the tribological behavior of DLC coatings at tool radii of dry deep drawing processes, ta-C and a-C:H coated tests cylinders were applied for strip bending rotation tests. As a reference, a polished, uncoated tool surface of similar roughness is additionally analyzed. Table 1 shows the experimental design for the investigation of modified tool surfaces.

Table 1. Test parameters.

Sheet material	Surface pressure	Tool surface		
		uncoated	ta-C	a-C:H
AA6014, AA5182	22 MPa	n = 3	n = 10	n = 10
DC04	45 MPa	n = 3	n = 10	n = 10
v_{rel} = 36 mm/s, ANG_{wrap} = 90°, ANG_{rot} = 90°, m_{dry} = 0,0 g/m²				

The surface pressures were set to 45 MPa for DC04 and 22 MPa for the aluminum alloys. These levels of contact pressure match the average of contact pressures along the die radius according to numerical simulations. Due to the appearance of wear on the uncoated tool surfaces after only a few samples, which leads to restrictions in the quantitative determination of the friction coefficient, the number of repetitions was set to n = 3. For a better understanding of the tribological long-term behavior of tool coatings, the number of stripes was set to n = 10. The velocity was set constant to the upper limit of the deployed device to 36 mm/s. The experiments were performed at room temperature. During deep drawing processes, an open tribosystem without repeated tool-workpiece contact is present. For this reason, the test cylinder is only rotated by 90°. Taking into account the wrap angle, 180° of the test cylinder was in contact with the sheet material after the test. All stripes for each sheet metal material are examined at the same area of the test cylinder. Due to initial fluctuations from stiction and saturation phases in the inlet area, the average torsional moment for the quantitative determination of the friction coefficient is determined at a rotation angle from 45° to 90°. Moreover, this procedure also excludes possible initial oscillations of the contact pressure during the calculation. Since the low vibration of approximately ± 0.5 % is negligible in the evaluation range, the previously set contact pressure is always used to determine the friction coefficient. Since the curve of the torsional moment over the rotation angle depends strongly on the parameter combination investigated, the entire curve profile of individual samples must always be analyzed to evaluate the friction conditions. Prior and after strip bending rotation test surface measurements are performed on tool and workpiece. The measuring is conducted tactile with the “Mar Surf GD 120” and optically with the confocal microscope “µSurf”. Additionally, photographs are taken from the tools to get an overall impression of the wear behavior in the contact area.

3. Results and discussion

3.1. Surface characterization before strip bending rotation test

The surface characterization of the tool and sheet before testing allows investigating the influence of surface texture on the friction coefficient and wear mechanisms. Fig. 2 shows the topography and roughness values in the initial state for the applied tools and workpiece materials.

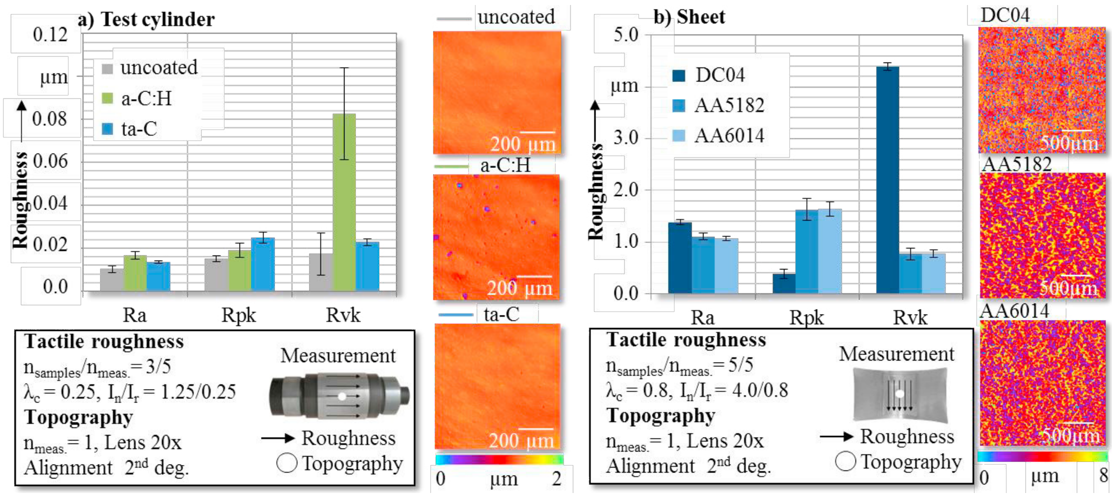

Fig. 2: Topography and roughness values for the used tools and sheet materials before testing.

Basically, the polished uncoated surfaces with an average Ra value of 0.009 ± 0.002 µm have the lowest roughness. The ta-C coated cylinders are slightly rougher with individual roughness peaks, that result in a Rpk value of 0.024 ± 0.005 µm. In the case of the a-C:H coated cylinders, isolated craters can be recognized due to the arc evaporation process of the Cr adhesion layer in the otherwise smooth surface, which leads to a high Rvk value of 0.067 ± 0.034 µm. The sheet materials all have an electrical discharge textured EDT surface. However, the confocal images of the surface topography and the specific roughness values illustrate the differences between the steel and aluminum alloys. While the surface of DC04 has a more plateau-like surface structure with deep valleys, the aluminum surfaces show a more irregular distribution of peaks and valleys. The Rpk values of around 1.63 µm illustrate the increased occurrence of profile peaks in the aluminum sheets compared to the steel sheets. The plateau-like surface texture accounts for the high Rvk value for DC04 of 4.393 µm.

3.2. Results of friction coefficient and surface analysis

With the aim of reducing friction and wear, the coating systems described in Chapter 2.1. are examined with regard to their tribological behavior during strip bending rotation tests. For a better understanding of the tribological behavior of coated and uncoated test cylinder in contact with varying sheet materials, the analysis of the friction coefficient μ over the individual samples is necessary. Fig. 3 shows the procedure for determining the mean friction coefficient as well as the corresponding results for each examination stage.

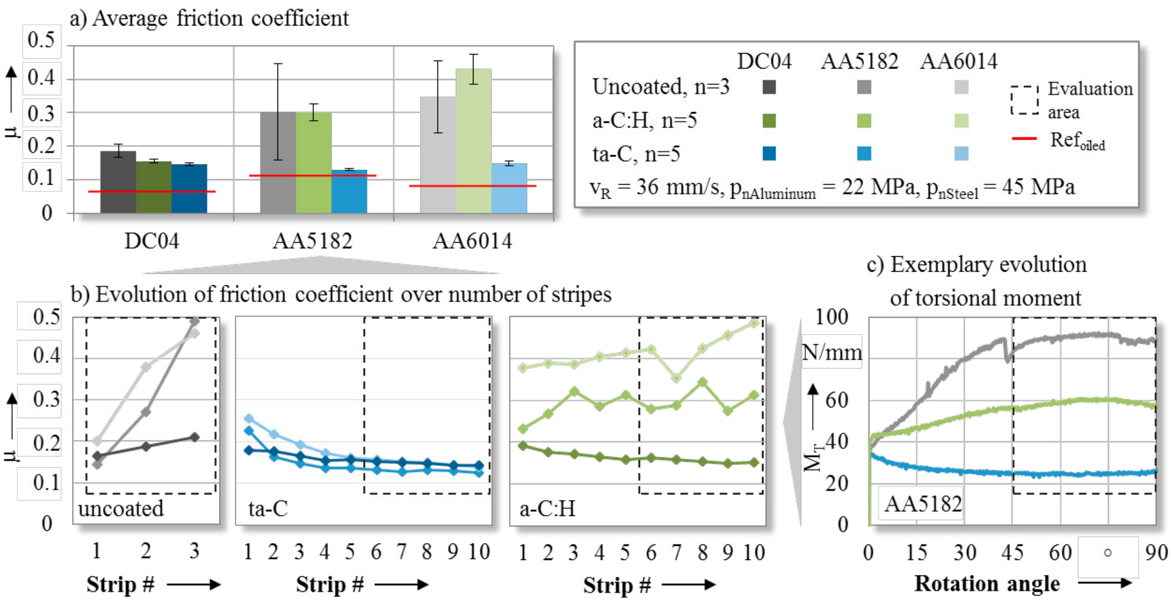

Fig. 3: Development of friction coefficient over the number of samples.

Fig. 3a) shows almost no influence of the tool coatings on the average friction coefficients for the zinc coated sheet material DC04 during dry contact, taking the standard deviation into account. The friction coefficients have an average value of around 0.16, which is nearly double as high as the reference Ref_{oiled} under lubricated conditions. Analogous to the preliminary flat strip drawing tests [5], higher friction coefficients result for the aluminum alloys without lubricant. Besides the chemical composition of the materials, main reason for the higher adhesion tendency of aluminum is its cubic face-centered lattice structure, compared to zinc with a hexagonal densely packed lattice structure. However, the ta-C coatings achieved a significant reduction of the friction coefficient compared to an uncoated tool surface. Due to the formation of an graphite like transfer layer of the ta-C coating during contact, which can act as solid lubricant [9], similar average friction coefficients as for DC04 are determined for both aluminum materials. In the case of a-C:H coatings, hydrogen contributes to the passivation of the free bonds and thus reduces the reactivity of the coating [10]. Nevertheless, the a-C:H coating leads, compared to ta-C, to a higher average friction coefficient of 0.43 ± 0.04 for AA6014 and 0.30 ± 0.03 for AA5182. The main reason for this is the rough surface, where the craters are potential initial points for aluminium adhesion and thus contribute to an increase in friction. For the initially smooth polished and uncoated surface, similarly high or even lower friction coefficients are achieved on average. The high standard deviation with respect to the individual samples however indicates the occurrence of substantial wear due to the direct tool-workpiece contact. Considering the friction coefficients for each sample, an increase of the friction coefficient by 2 to 2.5 times for the aluminum alloys can already be seen after the third sample (Fig. 3b). The relative low friction coefficient for the first sample is caused by the low roughness of the polished surface, as a lower tool roughness enables lower friction forces [8]. Due to the low adhesion tendency of zinc coated steel, the increase of the friction coefficient with uncoated surfaces is relatively low for DC04. In the case of the ta-C coating, a reduction of the friction coefficient can be recognized for each sheet material at higher repetition rates. From the fifth sample onwards, almost constant values can be observed, which is why they are used for the calculation of the mean friction coefficient. The significant reduction of the friction coefficient over the first five samples indicates a run-in behavior, which is typical for DLC coatings [11]. Possible reasons are a slight smoothing of the tool surface peaks during relative movement with the sheets as well as a change in the chemical composition of the transfer layer due to oxidation. This run-in behavior can also be detected for the a-C:H coating in contact with DC04. For the aluminum alloy AA6014, the friction coefficient increases almost constantly as the number of stripes increases, but significantly slighter compared to the tests with uncoated tool. For AA5182, the friction coefficient increases by 39 % after the third sample and then varies around a nearly constant value. In addition to the differences in the friction coefficient for each sample, a difference in the torque curve over the angle of rotation can be detected. Fig. 3c) exemplarily shows representative curves per tool surface for AA5182. For the ta-C coating, the torque drops after an inital overcoming of stiction and then remains steady over the rotation angle. In case of the uncoated and a-C:H coated surface, the torque increases analogous to the average friction coefficient, whereas the increase of the torque is significantly higher for uncoated tools. Fig. 4 shows the topographies of the contact partners after the last repetition test for the varied tool coatings and sheet materials. In order to analyze smoothing and wear effects, the ΔRpk values to the initial surfaces are additionally noted.

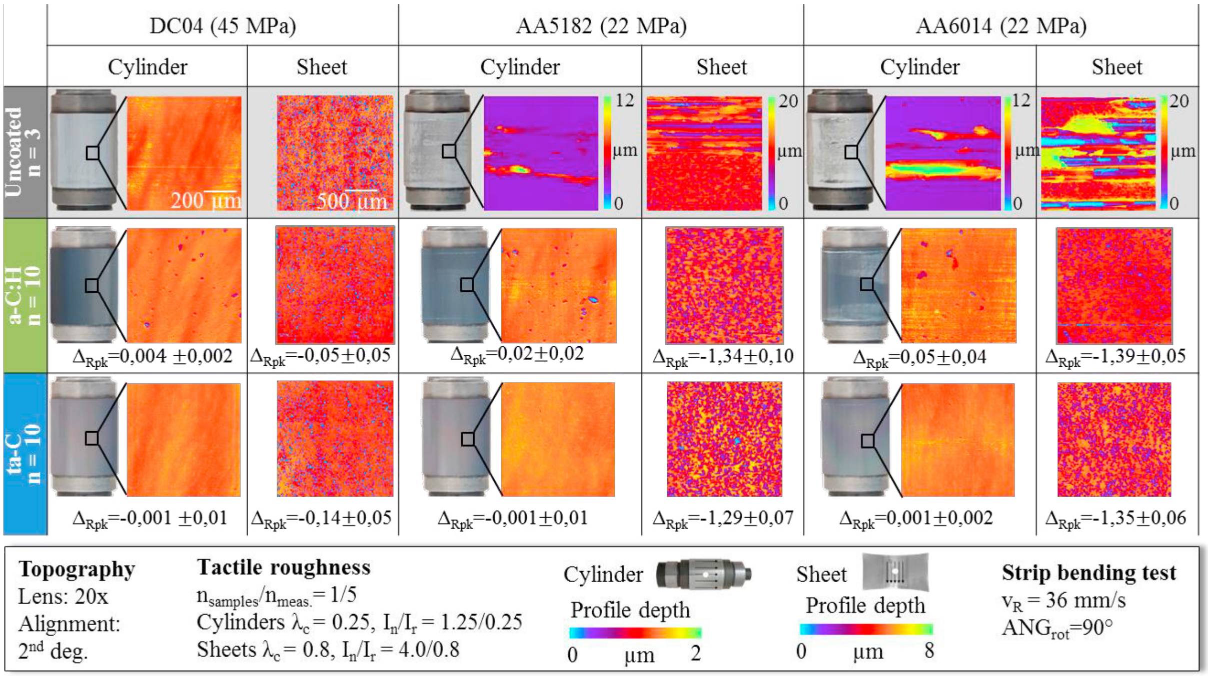

Fig. 4: Tool and sheet surfaces after strip bending rotation test.

The reference topographies of the uncoated test cylinders and the related sheet materials clarify the challenge of dry deep drawing processes as strong wear traces on the surfaces result especially for the tests with aluminum alloys. The tests with the coated tool surfaces show clearly better results with regard to the surface quality. No traces of wear could be detected for the a-C:H and ta-C coatings in contact to DC04. Regarding the aluminum alloys, the topography as well as the ΔRpk values for the a-C:H coated test cylinders indicate slight adhesions, which are more pronounced for AA6014 than for AA5182. This result also explains the development of the friction coefficient visualized in Fig. 3. As the a-C:H coatings have a high chemical inertness, the wear occurrence for a-C:H coatings may be due to individual defects in the a-C:H coating system, which cause locally increased contact stresses between the sheet and the test cylinder. As a result of the one-time occurrence of adhesive wear, adhering material particles are transported in a further relative movement over the surface in the direction of rotation, which subsequently leads to accumulated wear marks. Due to similar initial roughness values of the aluminum alloys, the reason for the higher adhesion tendency of AA6014 in comparison to AA5182 probably lies in the chemical composition of the alloys. In contrast to AA5182, AA6014 also shows minimal signs of profile elevations on the tool surface in the case of the ta-C coating. Since, however, no increase in the coefficient of friction can be observed, it has to be checked whether the profile elevations are caused by locally unevenness in the tool material or by aluminum adhesion. Due to the high standard deviation and low ΔRpk values, there is only a slight tendency of a smoothing of ta-C coated tool surface, which could explain the run-in behavior. Regarding the sheets, the material AA6014 tends to a greater level of sheet smoothing for both coatings compared to AA5182. Furthermore, the a-C:H coating also causes a greater reduction of the profile heights in the sheet material than the ta-C coating. This results in a change in the reduced peak height ΔRpk of -1,39 ± 0,05 µm for AA6014 in combination with a-C:H. In general, a higher tool surface roughness results in a higher smoothing of the sheet material due to enhanced interlocking of profile tips [8]. Since the a-C:H coating basically has a lower Rpk value compared to ta-C, the reason lies more in the occurrence of slight homogeneous wear marks on the cylinder, which causes an enhanced smoothening of the sheet profile tips by relative movement.

In order to investigate possible relationships between sheet surface smoothing by coated tools and friction coefficient, the aluminum alloy AA5182 was additionally tested with a surface pressure of 45 MPa. Increased surface pressure was applied for AA5182 and ta-C coating, as this combination did not show any wear marks in previous tests for aluminum alloys and is more sensitive than DC04. In order to exclude any run-in behavior, the same test cylinder as with 22 MPa was used. The red marks in Fig. 5 indicate the average friction coefficient per surface pressure (AVG p_n), whereas the green mark states the overall average (AVG overall) for the investigated sheet material and coating. Strip 1-3 represents the repetition samples 8-10 for 22 MPa, and 11-13 for 45 MPa.

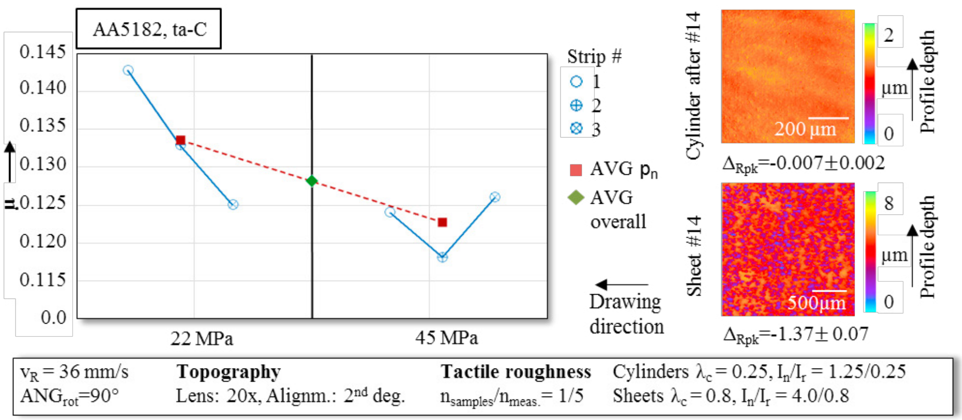

Fig. 5: Influence of increased surface pressure on friction coefficient and surface topography.

Taking into account a still constant reduction of the friction coefficient for repetition samples 8-12 as a result of the run-in behavior of ta-C, an increased surface pressure of 45 MPa has almost no influence on the friction coefficient. Since the sheet metal surface despite shows a clear smoothing with a ΔRpk of -1.37 ± 0.07 µm by higher contact normal stresses, it can be assumed that the smoothing of the sheet surface and thus the variation of the true contact area do not relate to the friction coefficient in this case. Furthermore, it must be noted that even with increased surface pressure and surface smoothing, no adhesive wear can be detected on the cylinder and the minimum friction coefficient of 0.12 for sample number 11 almost corresponds to the average friction coefficient of 0.10 for the tests with lubricant.

4. Conclusion and Outlook

With strip bending rotation tests, the application behavior of coated tool surfaces at critical radii area of deep drawing processes was investigated during dry contact with the sheet materials DC04 and the aluminum alloys AA5182 and AA6014. In contrast to previous flat strip drawing test, much higher contact pressures of up to 45 MPa were examined. The occurrence of wear especially for aluminum alloys in contact to the uncoated test cylinder illustrates the need for tool coatings at the critical radii area. In general, a significant reduction of wear and friction coefficient up to 0.12 results especially for ta-C coatings independent of the sheet material. When increasing the number of samples, a reduction of the friction coefficient by an average of 40 % can be observed after 10 samples due to the run-in behavior of DLC coatings. The a-C:H coating shows a higher dependence of the friction behavior on the sheet material. Especially for the AA6014, a higher coefficient of friction and increased wear marks were measured over the number of tests. For further investigations, a variation of coating properties needs to proof whether a-C:H coated tools could achieve a significant friction and wear reduction in contact with aluminum alloys at the radii area. The change of the coating technology for the deposition of the Cr adhesive layer from arc evaporation to sputtering has also to be analyzed with regard to the resulting surface topography and tribological behavior. Furthermore, [12] shows that a-C:H coatings have no aluminum adhesions during dry forming and are thus predestined for dry forming.

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