Investigation of surface finishing of carbon based coated tools for dry deep drawing of aluminium alloys

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Abstract. Global trends like growing environmental awareness and demand for resource efficiency motivate an abandonment of lubricants in metal forming. However, dry forming evokes increased friction and wear. Especially, dry deep drawing of aluminum alloys leads to intensive interaction between tool and workpiece due to its high adhesion tendency. One approach to improve the tribological behavior is the application of carbon based coatings. These coatings are characterized by high wear resistance. In order to investigate the potential of carbon based coatings for dry deep drawing, friction and wear behavior of different coating compositions are evaluated in strip drawing tests. This setup is used to model the tribological conditions in the flange area of deep drawing operations. The tribological behavior of tetrahedral amorphous (ta-C) and hydrogenated amorphous carbon coatings with and without tungsten modification (a-C:H:W, a-C:H) is investigated. The influence of tool topography is analyzed by applying different surface finishing. The results show reduced friction with decreased roughness for coated tools. Besides tool topography the coating type determines the tribological conditions. Smooth tools with ta-C and a-C:H coatings reveal low friction and prevent adhesive wear. In contrast, smooth a-C:H:W coated tools only lead to slight improvement compared to rough, uncoated specimen.

1. Introduction
Sheet metal forming operations like deep drawing represent very energy efficient processes [1]. However, the consumption of lubricants and detergents for cleaning procedures in conventional deep drawing processes has a negative impact on the environment. Dry forming aims at the abandonment of lubricants or utilization of volatile lubricants to eliminate cleaning and drying steps [2]. This reduces the number of production steps and time. Furthermore, the realization of lubricant-free forming would improve the sustainability and further increase the resource efficiency of manufacturing of sheet metal parts. Without lubrication, tool and workpiece surface have direct contact which leads to intensive interaction. This causes distinctive friction and wear. Especially, while forming aluminum alloys, adhesive wear needs to be considered in dry forming due to its high reactivity towards tool steel. Former investigations have shown that under laboratory and dry conditions the friction coefficient increases by factor of 10 to 20 depending on the aluminum alloy [3]. High friction leads to wear. In this regard, adhesion occurs as main wear mechanism at the initial tool-workpiece contact. Due to the adhesion and friction coefficients of 0.3 and higher lubricant-free deep drawing will lead to insufficient surface quality and tool wear. Thus, measures need to be taken to reduce adhesion
tendency of aluminum alloys towards tool steel. A promising approach for wear reduction under
lubricant-free conditions is the application of coatings as a separating layer between tool and
workpiece. Especially carbon based coatings are frequently used when friction reduction and increased
wear resistance are necessary [4]. Horiuchi et al. [5] figured out that applying diamond like carbon
based coatings could improve tribological conditions in terms of reduced friction coefficients and
punch load for deep drawing of 5xxx aluminum alloys. However, this investigation focused on blank-
sided coatings which seem not suitable for industrial applications. Few studies analyzed the influence
of substrate and coating topography on coating properties itself and tribological performance. Singh et
al. have analyzed the influence of varying steel substrate roughness values on the coating
characteristics [6]. Their results reveal that a higher substrate roughness leads to growing coating
roughness which causes a greater risk of cracks and surface damages during indentation tests. Thus, it
seems that smoother substrate and coating topographies are beneficial for the coating durability.
However, no studies have been conducted regarding the tribological performance of varying coating
roughness values. Numerical investigations from Lindholm et al. revealed that shape and distribution
of coating asperities influence the distribution of tensile stresses. Thereby, small and sharp asperities
cause spots of extreme load conditions [7]. Jiang and Arnell analyzed the wear behavior of different
coating roughness in ball-on-disc tests [8]. Their study showed that above an arithmetic mean
roughness value Ra of 0.93 µm wear rate and variation of test results increase rapidly. Due to its
closed tribological system, the results of a ball-on-disc tribometer cannot be transformed directly to
sheet metal forming operations. Sheet metal forming is characterized by an open tribological system
with planar contact conditions where constantly new sheet material is drawn through the contact zone.
Additionally, the ball was made out of tungsten carbide which means totally different material and
surface properties compared to sheet metal forming. Thus, the following investigation aims to evaluate
the tribological behavior under process relevant conditions for commonly used sheet materials like
aluminum alloys. By comparing ta-C, a-C:H:W and a-C:H coated with uncoated tools the effect of
coating type on friction and wear is evaluated. The influence of surface treatment before coating
deposition is investigated for a-C:H:W and a-C:H coatings compared to uncoated tools with different
surface roughness. Furthermore, for ta-C coated tools, the impact of tool topography is analyzed by
varying surface finishing after coating deposition. Overall goal of this study is to increase the
understanding of correlation between coating type, tool topography and resulting tribological
conditions.

2. Materials and coatings
In the present study the aluminum alloy AA5182 is selected as workpiece material with a sheet
thickness of 1 mm and an electrical discharge texture (EDT). AA5182 is commonly used in
automotive industry for inner car body parts [9]. The cold working steel 1.2379 (X155CrVMo12) is
chosen as tool material with a hardness of 60 HRC. To ensure that the hardness endures the coating
deposition a special hardening process suitable for post treatment at higher temperatures was applied.
All tools are machined with a combined lapping and polishing process with 9 µm grain size - in the
following called rough polishing - to achieve a plane surface without preferential direction. As second
surface finishing strategy polishing with a grain size of 1 µm – called smooth polishing – is applied.
The process chains are varied to investigate the influence of different finishing operations. The details
of surface finishing are explained in chapter 3.2.
Carbon based coatings are known for their low friction and high wear resistance. Thus, to prevent
tool sided wear under dry conditions three different carbon based coating types are investigated.
Coatings based on carbon with diamond like characteristics (DLC) are classified according to their
ratio of graphite (sp²), diamond (sp³) and hydrogen (H). In order to obtain a broad range of coating
properties and analyze their differing tribological behavior, coatings with a high sp³ ratio (ta-C) and a
low sp³ ratio containing hydrogen (a-C:H and a-C:H:W) are applied. The coating designs are
schematically shown in Figure 1. The ta-C coatings are deposited by using vacuum arc evaporation
(Laser-Arc-Technology). As adhesive film a Cr layer is deposited by sputtering on friction jaw
surfaces to guarantee a smooth ta-C coating. The functional ta-C layer has an average thickness of 1.2
µm and an average hardness of 4000 HV 0.001 was measured. Besides ta-C coatings, two kinds of
hydrogenated amorphous carbon coatings are analyzed. Beneath a-C:H:W and a-C:H coating an adhesive Cr layer and a WC interlayer is deposited. The chromium layer is deposited by using the arc evaporation method. The coating deposition is performed with the coating machine TT-300 from H-O-T by physical vapor deposition/plasma assisted chemical vapor deposition (PVD/PACVD). The a-C:H:W coating is deposited in an argon-acetylene atmosphere by reactive unbalanced magnetron sputtering of a binder-free WC target. Finally, for a-C:H coating a top layer without tungsten is deposited. The functional a-C:H:W coating shown in Figure 1 b) has an average thickness of 4 µm and an average hardness of 1000 HV 0.001. In comparison, the a-C:H coating with a thickness of 1.8 µm has a hardness of 2200 HV 0.001.

![Figure 1. Coating design of a) ta-C, b) a-C:H:W and c) a-C:H coating](image)

3. Experimental procedure

3.1. Test setup

In order to evaluate the tribological behavior of the different coating types and surface finishing strategies flat strip drawing tests are performed. This test setup models the tribological conditions of the area between blank holder and die in a conventional deep drawing process [10]. Thus, the strip drawing test is commonly used for tribological investigations in sheet metal forming. Furthermore, this setup enables a direct determination of friction coefficients and represents an open tribological system with a planar contact zone. In contrast to closed tribological systems, new sheet material is transferred constantly into the contact area like in real deep drawing processes. The schematic test setup is shown in Figure 2. A sheet metal strip is positioned between an upper fixed and a lower movable friction jaw. A defined normal force \( F_N \) is applied by moving the lower friction jaw upwards. The strip is clamped on one side and afterwards drawn through the friction jaws with a constant relative velocity \( v_{rel} \).

![Figure 2. Schematic test setup of flat strip drawing test](image)

Over a drawing length of 190 mm the drawing force \( F_{Draw} \) is recorded. This force corresponds to the sum of the upper and lower friction forces \( F_{FU} \) and \( F_{FL} \). The friction coefficient \( \mu \) can be calculated according to (1) by using the Coulomb friction law. Due to tool contact on both sides of the strip, only half of the friction force needs to be considered for determining \( \mu \).

\[
\mu = \frac{F_{FU} + F_{FL}}{2F_N} \quad (1)
\]
3.2. Experimental design

The experimental design is summarized in Table 1. A constant drawing velocity of 100 mm/s is used for all tests. This relative velocity represents a commonly applied relative velocity in sheet metal forming operations [11]. For each parameter combination, three strips are drawn to ensure a statistical certainty. In general, the level of contact pressure in the flange area of a deep drawing process varies between 1 and 10 MPa [11]. Former investigations revealed that under dry conditions with metallic bright tools contact pressures of up to 1.5 MPa can be realized without macroscopic deformation or failure of aluminum strips. Therefore, in a first run the contact pressure was set to this level. To proof the transferability of the experimental results to other process parameters, promising combinations of coating type and finishing operation which reveal low friction and no wear, are additionally tested at a pressure level of 3.0 MPa. In order to analyze the influence of varying surface topographies, for each coating type two different roughness levels are analyzed. As a reference, two uncoated friction jaws are investigated with a rougher and a smoother surface. All friction jaws were rough polished in a first step with an oil based diamond suspension with a grain size of 9 µm. Afterwards, the friction jaws 1-s to 4-s were polished in three steps with diamond suspension up to a minimum grain size of 1 µm. In the following, this process is called smooth polishing. Both pairs of ta-C coated friction jaws where smooth polished before applying the coating. The investigation of the ta-C coatings focuses on the influence of the surface treatment after the coating deposition. Therefore, the friction jaws 2-r were coated but not polished whereas 2-s were polished after the application of ta-C coating. The impact of surface treatment after coating deposition is not analyzed for a:C:H:W and a-C:H because previous studies showed that strip drawing is not possible without final surface treatment. Without polishing after coating deposition high friction causes fracture of the strips. Thus, merely the influence of a rough (3-r and 4-r) and smooth (3-s and 4-s) polishing before the coating deposition was analyzed. Before the strip drawing tests, all strips are cleaned in an aceton bath to remove the basic lubrication which is conventionally applied in the rolling mill as anticorrosive measure.

Table 1. Experimental design and parameters for strip drawing (velocity \( v_{rel} = 100 \text{ mm/s} \); \( n_{AA5182} = 3 \))

| Friction jaw | Coating type | Final surface treatment | Contact pressure (MPa) |
|--------------|--------------|------------------------|-----------------------|
| 1-r          | None         | Rough polishing        | 1.5                   |
| 1-s          | None         | Smooth polishing       | 1.5                   |
| 2-r          | ta-C         | Smooth polishing -> coating | 1.5       |
| 2-s          | ta-C         | Smooth polishing -> coating -> polishing | 1.5 / 3.0 |
| 3-r          | a-C:H:W      | Rough polishing -> coating -> polishing | 1.5       |
| 3-s          | a-C:H:W      | Smooth polishing -> coating -> polishing | 1.5       |
| 4-r          | a-C:H        | Rough polishing -> coating -> polishing | 1.5 / 3.0 |
| 4-s          | a-C:H        | Smooth polishing -> coating -> polishing | 1.5 / 3.0 |

4. Results

4.1. Surface characterization before strip drawing tests

Before performing strip drawing tests, tactile stylus and optical surface measurements of the tool surfaces are conducted with the “Mar Surf GD 120” and the nanofocus “μSurf” microscope, respectively. The topographies of the friction jaws after the final surface treatment are summarized in Figure 3. This figure gives a qualitative impression about the initial surface structure and the comparability of the surface properties between different friction jaws. The rough and smooth specimens reveal distinct differences in appearance of the surface structure. The rough polished tools without coating and with a:C:H:W and a-C:H coating show similar topographies whereas the rough configuration of the ta-C coating looks smoother. Reason is the smooth polishing step before the coating deposition. All smooth surfaces in Figure 3 reveal a similar and smooth topography. Small surface defects occurring during the growing of the coatings can be detected at the coated friction jaws. Especially, the smooth configuration of a-C:H depicts some distinct surface defects. However, all samples in the second row appear much smoother compared to the topographies above.
Figure 3. Initial tool topography of varied coating types and surface treatments

In addition to image-based measurements, two dimensional roughness measurements are performed for a quantitative evaluation. The arithmetic mean roughness Ra, the reduced peak height Rpk and the reduced valley depth Rvk were analyzed in Figure 4 for all friction jaws to get an impression of average roughness as well as of height and depth of asperities.

Figure 4. Initial tool roughness of varied coating types and surface treatments

Compared to the rough configurations, the values for Ra and Rpk are reduced significantly for the smooth variants. The development of Rvk shows a significant roughness reduction only achieved for the smooth surfaces without coating and with a-C:H:W coating. For ta-C coated jaws only a slight decrease of Rvk is accomplished with the polishing step after the coating deposition. The rough and smooth polished a-C:H coated tools reveal nearly the same level for the reduced valley depths. Reason for high Rvk values of smooth a-C:H surface is the occasional occurrence of approximately 1 µm deep holes in the top layer which could already been seen in the topography in Figure 3. These holes are caused by dirt particles or dust which could not be removed during the cleaning process which was performed before coating deposition. However, the height and distribution of roughness peaks is more important than those of valleys because the peaks are in direct contact with the sheet surface. To assure the comparability for all surface finishing strategies, the Rpk values vary in a small range between 0.02 and 0.03 µm for the smooth tools and between 0.10 and 0.13 µm for the rough tools. Only the rough configuration of ta-C coated tools reaches a much higher level of Rpk around 0.27 µm.
which is caused by the roughness increase during the coating deposition. Reasons for surface roughening are elevated temperatures during deposition, the formation of carbon clusters and the higher growing rate at asperities compared to valleys. Thus, the roughening during dynamic growth of the films depends on substrate roughness, temperature, gas mixture, ion energy and bias voltage.

4.2. Determination of friction coefficients
For the evaluation of tribological properties of the investigated tools, the recorded drawing forces during strip drawing are used to determine the friction coefficients. Figure 5 summarizes the friction coefficients for all topographies and coating types.

![Figure 5. Friction coefficients according to strip drawing tests for varied tool surfaces](image)

The friction coefficients vary in a broad range between 0.13 and 0.54. Under dry conditions with uncoated and rough tools a friction coefficient of 0.3 is determined. Smooth polishing of the metallic bright tool surface leads to further increase of friction up to a level of 0.42. In general, the coated tool surfaces could not decrease the friction coefficients compared to uncoated tools. The rough tools coated with ta-C and a-C:H:W cause even higher friction. A friction coefficient of 0.45 is reached for the rough ta-C coated jaws (2-r) whereas rough a-C:H:W coated tools (3-r) lead to a maximum friction of 0.54. Beneficial tribological conditions in terms of lower friction compared to uncoated tools could be achieved with all smooth polished, coated jaws and with rough polished a-C:H coated tools. A friction reduction of 0.04 is accomplished with smooth a-C:H:W coated tools compared to rough, metallic bright tools. However, considering the high standard deviation this is only a slight improvement. Depending on the surface finishing a-C:H coated jaws reveal general low friction coefficients between 0.20 and 0.15 (4-r and 4-s). The lowest friction coefficient is determined for smooth ta-C coated tools (2-r) with a friction coefficient of 0.13. Additionally, the tribological behavior of the tools with the lowest friction coefficients (2-s, 4-r and 4-s) is analyzed at a higher contact pressure of 3.0 MPa. Before these tests, the jaws where prepared by cleaning with acetone without further mechanical treatment. The resulting friction coefficients for both levels of pressure are compared in Figure 6. The tests with smooth ta-C and a-C:H tool surfaces reveal almost the same level of friction for both contact pressures. A slight increase of friction coefficient from 0.20 to 0.23 is determined for rough a-C:H jaws at the higher pressure of 3.0 MPa. Thus, at the relevant pressure levels in the flange area of deep drawing processes the investigated tribological systems (2-s, 4-r and 4-s) assure stable friction conditions.
Figure 6. Friction coefficient for 1.5 and 3.0 MPa for smooth ta-C coated jaws and a-C:H coated jaws

4.3. Surface characterization after strip drawing tests
In order to evaluate tool sided wear a surface characterization was performed after strip drawing tests at 1.5 MPa contact pressure. Photographs and topography measurements need to be considered for a comprehensive wear evaluation, because topography measurements with a size of 0.8 mm x 0.8 mm are not representative for the whole contact area with a size of 100 mm x 55 mm. As the determined friction coefficients vary in a wide range between 0.13 and 0.54 the wear distribution varies as well for each jaw. Pictures are taken from each tool to assess the complete contact area of 100 mm x 55 mm. The contact surface of the friction jaws after strip drawing is represented in Figure 7.

Figure 7. Photographs of tool surfaces after strip drawing tests

Adhesion could be identified as main wear mechanism. Both configurations of metallic bright jaws reveal adhesive wear. The smooth and uncoated tool surface reveals a higher amount of adhesion. Adhesion causes local deformation of the strip which increases the resistance against relative movement and thus leads to higher friction coefficients like for the smooth uncoated tools. For ta-C coated jaws a high amount of adhesive aluminum particles is detected for the rough topography whereas no wear occurs on the smooth surface. Distinctive wear arises for tools with tungsten modified coatings. A smaller amount of adhesion concentrated in the middle of the friction jaw can be found at the smooth tool whereas almost the complete contact area is covered with aluminum adhesion for rough a-C:H:W coated tools. Friction jaws coated with a-C:H display no visible signs of wear, regardless of surface finishing. Overall, the experiments which resulted in the highest friction levels (1-s, 2-r and 3-r) reveal a high amount of adhesion. The configurations ta-C with smooth surface and both a-C:H variants which resulted in low friction between 0.13 and 0.23 show no visible signs of wear. Besides photographs, the topographies of the tool surfaces are characterized after the tests using confocal microscopy. These measurements are performed to get information about the height of wear marks. Furthermore, the jaws which revealed no macroscopic adhesion are analyzed for microscopic signs of wear. For each pair of friction jaws one topography measurement is exemplarily shown in Figure 8. It could be assured that smooth, ta-C (2-s) and a-C:H coated jaws (4-r and 4-s) prevent initial adhesion also at a µm-scale. An increased profile depth is measured for metallic bright (1-r and 1-s) and a-C:H:W coated (3-r and 3-s) as well as rough, ta-C coated jaws (2-r). The adhesion height on
metallic bright, smooth jaws reaches a level of 20 µm. Adhesive wear tracks for rough, uncoated and rough, ta-C and both a-C:H:W coated jaws reveal a maximum profile depth of around 10 µm.

Figure 8. Topographies of tool surfaces after strip drawing tests

5. Discussion
By varying coating type and final surface treatment, friction coefficients can be varied in a broad range under dry conditions. The general relation between surface roughness and friction development is summarized in Figure 9.

Figure 9. Relation between reduced peak height Rpk of tools and determined friction coefficients

The coating application was performed to reduce friction and adhesion, because the carbon based coatings act as separating layer between tool steel and sheet material. Thus, the coatings substitute the detaching function which is conventionally fulfilled by lubricants. The successful prevention of adhesive wear depends on coating type and roughness of the coated surface. Besides chemical properties like surface free energy and electrochemical potentials, adhesion tendency is related to material hardness [12]. Materials with higher hardness evoke higher internal metal-metal bond energies which lead to increased resistance towards adhesion [13]. This correlation might explain the friction development for smooth surfaces. The metallic bright specimen reveals the lowest hardness of about 700 HV causing the highest adhesion and friction coefficient. In contrast, ta-C coated tools which have the highest hardness result in lowest friction and no adhesive wear. Additionally, for the smooth variants the friction increases with growing amount of metallic material on the tool surface. Thus, the highest friction is measured for uncoated jaws and the lowest for ta-C and a-C:H coatings without any metallic phase. Looking at the specimens with higher roughness this correlation is not entirely valid anymore. Here, the influence of mechanical interaction of contacting asperities seems predominant for coated surfaces. The higher hardness of coatings in combination with increased roughness leads to high local stresses which cause break out of microscopic particles of the brittle surface. Evidence for this effect might be the growing arithmetic mean roughness from 16% to 26% comparing the initial surface with the surface after strip drawing tests in areas without visible adhesion. An increased roughness could not be measured for uncoated specimens. Additionally, higher roughness peaks cause a rising interlocking of roughness asperities. Thus, the resistance against
relative movement increases which leads to higher friction coefficients for rough, coated specimens. Besides mechanical and topographical properties, the determined friction depends as well on chemical properties of the coating. Tungsten modified coatings result in an insufficient tribological behavior. For rough and smooth configurations approximately the same values of Rpk were measured for a-C:H:W and a-C:H coatings. However, the friction coefficient is more than 2.5 times higher for rough a-C:H:W coatings and 1.7 times higher for smooth a-C:H:W compared to a-C:H coatings. Reason for these differences might be a higher affinity of aluminum towards the metallic components in tungsten modified coatings. Additionally, a-C:H:W coatings reveal only half the hardness of a-C:H which promote growing adhesion tendency. As a reference, experiments with rough and smooth uncoated jaws were conducted. Contrary to the results of coated tools, a smoother, metallic bright surface lead to an increase of friction of 39% which is caused by growing adhesive wear due to increased real contact area. When tool roughness decreases, the real contact area increases as shown in Figure 10. Hence, an increased contact area leads to a growing target area for adhesion occurrence and thus results in higher friction in combination with increased wear. In contrast, smooth, coated surfaces did not result in higher friction because the coating itself functions as wear-resistant, separating layer between tool steel and sheet material. This reduces adhesion for a-C:H:W and prevents adhesion in case of ta-C and a-C:H coatings. At similar peak heights, smooth ta-C and a-C:H coatings reveal low friction and no wear. However, with ta-C coatings a 16% lower friction coefficient is achieved. This example and the results for a-C:H:W coatings show that not only low roughness but also a suitable coating type has to be considered to improve the tribological conditions in dry contacts.

Figure 10. Contact area between AA5182 and metallic bright jaws for rough and smooth surfaces

6. Conclusion and outlook
In this paper the tribological properties in terms of sliding friction coefficients and wear behavior were characterized for different coating types. Moreover, the influence of varied surface topographies was investigated. As a reference, metallic bright tools were analyzed. To determine friction coefficients under close to forming conditions, flat strip drawing tests were performed. In general, the properties of a tribological system depend on chemical bonds and physical forces [12]. Thus, the tribological behavior revealed a strong dependency on surface roughness and coating type. Whether chemical properties like bonding energies and reactivity or mechanical properties like interlocking asperities dominate the frictional behavior depends on their specific characteristics. The relation of reduced peak height Rpk and friction coefficient is reverse for coated and uncoated tools. The investigated aluminum alloy shows a high affinity towards metallic bright jaws due to high chemical bonding forces between aluminum and steel. A reduction of surface roughness increased the real contact area and consequently the target area for adhesion occurrence. Thus, applying smoother tool surfaces leads to increased adhesive wear and friction in case of uncoated jaws. Coated specimens revealed lower friction at a decreased level of surface roughness. Increased friction and partly occurrence of adhesion is measured for rough coated tools. Here, adhesion is mainly caused by interlocking of roughness asperities in relation with high local stresses at contacting roughness peaks. For tungsten modified coatings, both, chemical and mechanical bonding occurs. Therefore, the friction coefficient is significantly higher for smooth and rough surfaces compared to the other coating types. A high chemical inertness occurs for a-C:H and ta-C which resulted in beneficial tribological behavior for smooth surfaces. In case of a-C:H coatings even the rough configuration showed low friction and no visible adhesion. In contrast, the more than two times rougher ta-C coatings reveal relatively high
friction and adhesion. Thus, applying ta-C coatings without a surface treatment after coating deposition could not be recommended. There must be a critical value of Rpk between 0.11 and 0.27 µm at which the interlocking and the local contact stresses are too high to further prevent adhesion even with low reactive coatings. Further tests need to be conducted with surface qualities between these roughness levels to identify a promising compromise between duration and costs for surface finishing and tribological behavior. In order to achieve the overall goal of lubricant-free deep drawing operations with aluminum alloys suitable surface modifications need to be developed. Experiments with uncoated tools showed that even at low pressure and with low and high surface roughness severe galling occurs. Carbon based coatings could improve the tribological properties in direct contact with aluminum alloys depending on their chemical, mechanical and topographical properties. First of all, coating types with low reactivity and without metallic elements revealed better tribological conditions. Besides coating structure and doping elements, a surface treatment after coating deposition and general low coating roughness is beneficial to further reduce friction under dry conditions. Moreover, high coating hardness has a positive impact on friction and wear behavior. Further investigations with non-metallic doping elements in ta-C and a-C:H coatings need to be performed to evaluate if a further friction reduction is possible.

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