Self-Lubricating Physical Vapor Deposition Coatings for Dry Cold Massive Forming

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Cold massive forming, particularly forward extrusion of steel, is characterized by high material utilization, product quality, and resource efficiency. Currently, enormous quantities of mostly ecologically harmful lubricants are required, leading to the demand for lubricant-free cold forming. Furthermore, cost savings are achievable due to shorter lead times. However, the requirements for the tools cannot be met without the application of wear-resistant and friction-reducing hard coatings. The self-lubricating hard coatings (Cr,Al)N + Mo:S and (Cr,Al)N + W:S with attuned material design deposited by physical vapor deposition (PVD) offer high potential for the realization of dry cold forming of steel. The process chain for the comprehensive characterization of the developed coating systems comprises analyses of coating and compound properties as well as two different model tests to determine the tribological behavior. One of the used tribometers represents an open tribological system, which is particularly suitable for simulating the loads occurring during cold massive forming of steel. The analyses reveal that with Mo and S modified coatings exhibit higher potential for ecologically sustainable cold forming due to their better mechanical properties and compound properties between the coatings and the cold work steel substrate compared with W and S modified coatings.

1. Introduction

Cold massive forming of steel is of great importance due to its potential for high material utilization and considerable energy and resource efficiency.[1] In particular, the full-forward-extrusion process is of great importance for the automotive industry.[2] To reduce friction between forming tools and workpieces during cold forming processes, high quantities of lubricants and applied phosphate films of the semifinished products are used.[3,4] However, due to legislative, economic, and ecological reasons, there is a huge interest in lubricant-free cold forming.[5] To meet this goal, self-lubricating tool coatings deposited by physical vapor deposition (PVD) can be applied as an alternative.[6] Such coatings contribute to a reduction of friction forces between forming tools and workpieces, and therefore to reduced wear of tools. The self-lubricating properties of these PVD coatings are based on the formation of reaction layers consisting of transition metal dichalcogenides (TMDs) under tribological stress.[7] Tungsten disulfide (WS₂)[8] and molybdenum disulfide (MoS₂)[9–11] are two types of TMDs, which are increasingly in the focus of attention in this area of research. In such TMD, the crystallographic layers are bonded together with weak Van der Waals forces, thus leading to a low shear strength and subsequently to low friction.[12] However, self-lubricating coatings based on TMD cannot withstand the mechanical loads of full forward extrusion because contact normal stresses of up to \( \sigma_N \approx 3000 \text{ MPa} \) occur.[14] This is attributed to the weak mechanical properties, e.g., indentation hardness \( H_I \leq 8 \text{ GPa} \) and low adhesion strength between the TMD-based coatings and substrate materials[7] compared with hard coatings.[14] For this reason, there is an effort to combine TMD with a wear-resistant hard phase to provide resistance to abrasive wear combined with friction reduction. The ternary coating system (Cr,Al)N deposited by PVD is a promising candidate for this purpose as it exhibits a high hardness, good abrasion wear resistance and high corrosion resistance.[15] These coating systems can be deposited with PVD technologies such as direct current magnetron sputtering (DCMS) or high-power pulsed magnetron sputtering (HPPMS). Compared with the HPPMS technology, DCMS is characterized by high deposition rates, which is an important cost factor for industrial coating processes.[16] On the contrary, the HPPMS technology generally operates at short pulse lengths of several tens of microseconds and with frequencies in between of 300 Hz \( \leq f_{\text{pulse}} \leq 4 \text{ kHz} \).[17] Therefore, HPPMS provides high peak current and high ionization degree within the plasma, which is usually much higher than conventional DCMS. This leads to higher plasma densities.
which results in deposition of coatings with dense microstructure and good mechanical properties.\textsuperscript{[18]} Furthermore, HPPMS is advantageous for the deposition of coatings on complex tool geometries, in particular for the coating deposition on geometries with high aspect ratios, e.g. forming dies. As the PVD technology exhibits a strong line of sight characteristic during the deposition process, the HPPMS technology supports coating deposition on complex geometries due to the high-energetic plasma compared with DCMS.\textsuperscript{[17]} The combination of DCMS and HPPMS in a hybrid process combines the advantages of both processes.\textsuperscript{[19]} The main focus of this article is therefore to use the hybrid technology DCMS /HPPMS for the deposition of a self-lubricating hard coating systems on complex shaped tools. In the scope of this work, the influence of the elements Mo and S as well as W and S incorporated in the (Cr,Al)N hard coating on the resulting properties is investigated. Furthermore, the coatings produced are examined with regard to their system properties in closed and open tribological systems using pin-on-disc (PoD) and pin-on-cylinder (PoC) tribometers. An open tribological system as in the PoC is characterized by the fact that the basic body is continuously in contact with an unworn surface of the counterpart. This is better suited for the simulation of the stress collective in the cold massive forming process as it occurs in the full-forward-extrusion process.

2. Experimental Section

The cold work steel AISI D2 (X155CrMoV12, DIN 1.2379) was used as substrate material because it is commonly used for cold forming tools.\textsuperscript{[20]} The samples were hardened to (60 ± 1) hardness rockwell cone and have a diameter of $\phi_{\text{sub}} = 25$ mm and a thickness of $t = 8$ mm. The surface was polished to an arithmetic mean roughness of $R_a = 0.02 \mu m$. For the investigation of the coating thickness $s$ and the surface roughness dependent on the bore depth of the forming die, an experimental tool was designed with the same geometry as the full-forward-rod-extrusion die. The opening diameter was $\phi_{\text{opening}} = 30$ mm, the final diameter was $\phi_{\text{final}} = 20$ mm, and the opening angle of the die shoulder was $\alpha = 45^\circ$. The total bore depth of the die accounted for $d = 50$ mm. Four cemented carbide WC-Co substrates THM (Kennametal Widia Productions GmbH & Co. KG, Essen, Germany) were fixed at four specific positions P1–P4 along the longitudinal axis of the experimental tool, thus allowing these to be subsequently examined with respect to the coating properties. The (Cr,Al)N + W: S and (Cr,Al)N + Mo:S coatings were deposited in an industrial scale coating unit CC800/9 Custom (CemeCon AG, Wuerseelen, Germany). The coating unit was equipped with four DCMS and two HPPMS cathodes. The arrangement of the cathodes and a schematic of the deposition chamber are shown in Figure 1a.

For the deposition, five CrAl20 targets (Cr-base plate with 20 Al plugs) (CemeCon AG) with a purity of $w_{\text{Cr}} = 99.9\%$, $w_{\text{Al}} = 99.5\%$, and one correspondingly WS2 and MoS2 target with a purity of $w_{\text{WS}2, \text{MoS}2} = 99.5\%$ were used. These were mounted on one of the four DCMS power supplies. During deposition, the samples were moved in a one-folded rotation. To investigate the influence of the incorporated elements W and S as well as Mo and S on the mechanical properties, the adhesion strength between coating and substrate and the tribological behavior, four different coating systems were deposited. In previous works, two (Cr,Al)N + Mo:S coatings, which were deposited with a substrate bias voltage of $U_{\text{bias}} = -100$ V and $U_{\text{bias}} = -75$ V, had shown high potential as tool coatings for the application of dry cold forming of steel due to good adhesion between coating and substrate\textsuperscript{[11]} as well as tribological behavior.\textsuperscript{[10]} The two coatings (Cr,Al)N + W:S presented in this work were deposited with the same parameters as the coatings (Cr,Al) N + Mo:S to investigate the influence of the incorporated refractory elements W and Mo. These four coatings were deposited using a metallic (Cr,Al) bond coat and a (Cr,Al)N interlayer. The process parameters are shown in Table 1.

The deposited coatings with $U_{\text{bias}} = -100$ V and $U_{\text{bias}} = -75$ V were termed in the following as W100, W75, Mo100, and Mo75. The nomenclature was dependent on the incorporated refractory elements W and Mo and the bias voltage $U_{\text{bias}}$ (Table 2).

To evaluate the morphology and thickness of the coatings, micrographs of fractured cross sections were taken using secondary electrons detector in a scanning electron microscope (SEM) ZEISS DSM 982 Gemini (Carl Zeiss AG, Oberkochen, Germany). Measurements of surface roughness were performed according to ISO 4287 by means of a confocal laser scanning microscope (CLSM) Keyence VK-X210, Tokyo, Japan. The chemical composition was analyzed by energy dispersive X-Ray spectroscopy (EDS) in the beam path of the SEM. The SEM and EDS measurements were conducted at the Central Facility for Electron Microscopy of the RWTH Aachen University. A Nanoindenter TI 950 (Bruker

![Figure 1](image-url). a) Schematic of coating deposition setup and b) schematic of the PoC tribometer.
Table 1. Process parameters for deposition of coating system (Cr,Al)
N + W:S and (Cr,Al)N + Mo:S deposited with \( U_{\text{bias}} = 100 \) V and \( U_{\text{bias}} = 75 \) V.

| Process parameters       | Unit | Value |
|--------------------------|------|-------|
| Max. substrate temperature, \( T \) | °C   | 480   |
| Pressure, \( p \)         | mPa  | 710   |
| Argon flux, \( j_(Ar) \)  | sccm | 200   |
| Nitrogen flux, \( j_(N_2) \) | sccm | Pressure controlled |
| DCMS cathode power W52, Mo52, \( P \) | kW  | 2     |
| DCMS cathode power CrAl20, P | kW  | 3     |
| HPPMS mean cathode power CrAl20, P | kW  | 5     |
| Pulse frequency, \( f_(pulse) \) | Hz   | 500   |
| Pulse length, \( t_(p) \) | μs  | 40    |
| Bias voltage, \( U_{\text{bias}} \) | V   | \(-100/-75\) |

Table 2. Nomenclature of the samples examined.

| \( U_{\text{bias}} \) [V] | (Cr,Al)N + W:S | (Cr,Al)N + Mo:S |
|--------------------------|----------------|----------------|
| –100                     | W100           | Mo100          |
| –75                      | W75            | Mo75           |

Corporation, Billerica, MA, USA) with a Berkovich indenter was applied for the determination of the mechanical properties indentation hardness \( H_T \) and indentation modulus \( E_T \). The constant indentation force used was \( F = 10 \) mN. The indentation depth was kept below 10% of the coating thickness. Calculations of \( E_T \) are based on Oliver and Pharr’s equations.[21] A constant Poisson’s ratio of \( \nu = 0.25 \) was assumed for the coatings according to the previous work.[22] In addition, the plastic work \( W_{pl} \) and elastic work \( W_{el} \) were determined from the nanoindentation force–displacement curves according to the previous work,[23] to determine the ratio of plastic work to total work \( W_{pl}/W_{total} \). The lower the ratio, the greater is the resistance to plastic deformation.

Adhesion strength of the investigated compounds substrate/coating was evaluated using Rockwell indentation and scratch test. Rockwell tests were performed and evaluated according to DIN 4856, followed by analyses of residual indents by CLSM. The adhesion strength between substrate and coating could be classified into adhesion classes HF 1–HF 6 depending on the damage phenomena at the edge of the Rockwell indenter. The more extensive the damage, the higher the adhesion class. A quantitative analysis of adhesion strength between substrate and coating was achieved by scratch testing according to ISO 20502 (DIN EN 1071-3). In this regard, the scratches were performed at different loads, and the adhesion between substrate and coating was quantified by CLSM through determination of the critical scratch loads \( L_{C1}−L_{C3} \). The critical scratch loads \( L_{C1}−L_{C3} \) were determined depending on the extent of the damage phenomena in and at the edge of the scratch track. The higher the critical scratch loads, the better the adhesion strength between coating and substrate.

In addition, tribological tests were performed in a PoD tribometer (Anton Paar, Peseux, Switzerland) (former CSM instruments SA). Pins of hot rolled AISI 5115 (16MnCr5, DIN 1.7131) with a radius of \( r_{pin, PoD} = 6 \) mm and a hardness of \( H = 200 \) HV were chosen as counterparts. AISI 5115 is one of the typical semifinished products in cold forming.[23] Pins were pressed in off-center position onto the uncoated reference specimen and the coated samples with a track radius of \( r_{PoD} = 5 \) mm. A constant normal load of \( F_N = 10 \) N was chosen for the PoD tests. The tests were performed at room temperature \( T = 23 \) °C. Relative velocity was \( v_{rel} = 5 \) cm s\(^{-1}\). The subsequent wear analyses were conducted using CLSM. The PoD test was performed to assess the self-lubricating, friction-reducing properties of the various coatings as dependent on the incorporated refractory metals W and Mo and the bias voltage.

Furthermore, a PoC tribometer, which was recently developed by the Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, was used to analyze the tribological behavior in an open tribological system. Unlike the PoD tribometer, the pin that simulated the tool was always in contact with an unworn surface of the counterpart. Thus, compared with the PoD test, the PoC test provided a more accurate simulation of the contact conditions that occurred during full forward extrusion. In comparison to the PoD test, the pins consisted of hardened tool material AISI D2 and exhibited a radius of \( r_{PoC} = 15 \) mm. A constant normal load of \( F_N = 2600 \) N was applied by a hydraulic actuator. The counterpart cylinder consisted of the workpiece material AISI 5115 with a radius of \( r_{cylinder} = 50 \) mm. The coatings to be examined were applied to the pin. The PoC tribometer was installed on a turning lathe. The workpiece was rotating with \( n = 19 \) min\(^{-1}\) and the pin was moving in axial direction with a defined feed of \( f = 8 \) mm. The tests were performed at room temperature \( T = 23 \) °C. In contrast to the PoD, the coated pin was continuous in contact with an unworn surface of the counterpart. Thus, the PoC simulated the conditions of contact while cold forming in a better way than the PoD. A schematic illustration is shown in Figure 1b. Furthermore, the PoC could be used to assess the resistance to adhesive cold welds due to the high applied normal force of \( F_N = 2600 \) N using a hydraulic actuator. This is of great importance because adhesive tool wear has a great influence on the resulting component quality.

3. Results and Discussion

3.1. Coating Properties

The morphology and the thickness of the coatings W100 and W75 were analyzed by SEM cross-sectional micrographs (Figure 2). W100 exhibits a thickness of \( t = 2.2 \) μm and thickness of W75 is \( t = 2.1 \) μm.

Based on the SEM analyses, both coatings reveal a fine columnar morphology. The surface topography is smooth and homogeneous with \( R_a = 0.03 \) μm. The cross-sectional micrographs of the coatings Mo100 and Mo75 reveal comparable coating growth compared with W100 and W75.[11] A metallic bond coat (Cr,Al) and a nitride interlayer (Cr,Al)N were applied to improve the adhesion of the top layer to the substrate. Table 3 shows the chemical composition of the deposited coatings. These were determined by means of EDS area measurements of the coating surfaces. The elements Cr, Al, S, and W or Mo were quantified. The nitride content \( x_N \) was not taken into account because it is not quantifiable by means of EDS.
Figure 2. SEM cross-sectional micrographs of the a) W100 and b) W75 coated substrates AISI D2.

The four coatings (W100, W75, Mo100, and Mo75) exhibit a relative constant chromium and aluminum content with $x_{\text{Cr}} \approx 78$ at% and $x_{\text{Al}} \approx 10$ at%. Furthermore, a trend can be seen that the deposition rate of Mo is slightly lower than W. However, the sulfur content shows a correlation to the bias voltage. The decrease in the bias voltage $U_{\text{bias}}$ leads to an increase in the sulfur content $x_S$. An increase in the sulfur content of $\Delta x_S = +24$ at% occurs from sample W100 to W75 and an increase in $\Delta x_S = +89$ at% occurs from sample Mo100 to Mo75. This increase is attributable to the resputtering effect. During the coating deposition, also a resputtering of the sulfur takes place, which is mainly caused by accelerated argon ions. Particularly, the resputtering of the sulfur should be considered, due to the comparable atomic radius and mass of argon and sulfur. The amount of such resputterings depends on the kinetic energy of the argon ion.\(^\text{[24]}\) Here, higher values of bias voltage $U_{\text{bias}}$ lead to higher velocities, and thus to the higher kinetic energy of argon ions.\(^\text{[25]}\) Therefore, with an increase in bias voltage from $U_{\text{bias}} = -75$ V to $U_{\text{bias}} = -100$ V more resputtering of sulfur takes place.

The arithmetic mean roughnesses and mechanical properties indentation hardness $H_{\text{IT}}$, indentation modulus $E_{\text{IT}}$, and ratio of plastic work to total work $W_{\text{pl}}/W_{\text{total}}$ are shown in Table 4. The highest resistance to the indenter is exhibited by coatings W100 and Mo100, which have been deposited with a bias voltage of $U_{\text{bias}} = -100$ V. A trend can be seen that the indentation modulus $E_{\text{IT}}$ of the coatings increases with increasing bias voltage $U_{\text{bias}}$. Furthermore, Mo75 has the highest ratio $W_{\text{pl}}/W_{\text{total}} = 49.9$\% and Mo100 has the lowest ratio $W_{\text{pl}}/W_{\text{total}} = 42.5$\%. The arithmetic surface roughness is $R_a = 0.03 \mu m$ for the W incorporated coatings and $R_a = 0.02 \mu m$ for the Mo incorporated coatings.

For the investigations on the coating thickness distribution along the longitudinal axis of the forming tool, the coated substrates positioned at P1–P4 of the experimental tool were investigated (Figure 3). The front and back side of each sample was subsequently analyzed by means of SEM. As both coating systems W100 and W75 exhibit similar trends regarding the coating morphology as a function of the bore depth, only the corresponding results to the coating system W100 will be presented in this work. Cross-sectional micrographs of Mo100 are published in a previous publication.\(^\text{[11]}\) Figure 3a–d shows the SEM cross sectional micrographs of W100 coated substrates at positions P1–P4B. The morphology of the coating differs slightly as a function of the bore depth. In this regard, the specimen at position P1 reveals the maximum deviation from a vertical orientation of coating’s columns, which will be generally observed for the samples located parallel to the targets in coating unit. The microstructural coating’s columns at P1 exhibit an orientation of $\theta = 60^\circ$ (Figure 3a,b). By a change in the orientation of substrate’s surface with respect to the targets, the coating at P2B and P2B exhibits a fine and dense morphology (Figure 3c,d).

Within the position P3, the morphology changes again to a columnar microstructure. However, the inclination of the columns approaches gradually to $\theta = 115^\circ$ along the longitudinal axis of the experimental tool. At position P4B, some portions of the sputtered atoms enter the experimental tool from the back side and condense additionally onto the substrate. This additional coating deposition leads to reversely inclined columns at P4B.

Furthermore, Figure 3 also shows the coating thickness distribution along the tool contour of the various coating variants W100, W75, Mo100, and Mo75 as a function of the bore depth of the experimental tool which exhibit the same geometry as an
actual full-forward-rod-extrusion die. The coatings reveal a coating thickness distribution similar to each other. However, the deposition rates of the W100 and W75 coating processes are slightly higher than the Mo and S modified coatings. As the aspect ratio $AR$ increases, the coating thickness decreases along the longitudinal axis of the experimental tool to a hole depth of $d_{bore} = 33$ mm, except the die shoulder ($P_{2F}$ and $P_{2B}$). The coating thickness increases due to the direct line-of-sight of the die shoulder, which has an angle of $\alpha = 45$ to the targets. In contrast, the specimens $P_1$, $P_3$, and $P_4$ are aligned perpendicular to the target. To protect the tool against wear and increased friction between the workpiece, it is necessary to apply the self-lubricating coating homogeneously over the entire tool surface with comparable coating growth. In general, it can be noted that hybrid DCMS/HPPMS technology provides a quite homogeneous self-lubricating tool coating on bore flanks with high aspect ratios, thus the forming tools are protected against high wear.

3.2. Compound Properties

For the application of self-lubricating coatings on highly loaded tools, the compound adhesion between coating and cold work steel substrate exhibits a key role to ensure stable cold forming processes. Due to the complex tool geometries with sharp contours and small radius at the extrusion shoulder, good adhesion strength between coating and substrate is indispensable. The Rockwell indents of the compounds W100/AISI D2 and W75/AISI D2 reveal spallings and cracks at the edge of the indents (Figure 4). The adhesion classes of the Rockwell indentations of the compounds Mo100/AISI D2 and Mo75/AISI D2 can be assigned to HF 1 and HF 2. In contrast, the W and S incorporated coating systems W100 and W75 exhibit a significantly lower adhesion between coating and substrate with HF 4 and HF 5.

Scratch tests were performed for a more accurate quantification of the compound adhesion between substrate and coating. The critical loads $L_{C1}$ to $L_{C3}$ of W100/AISI D2 and W75/AISI D2 were determined to be $L_{C1} = 20$ N, $L_{C2} = 30$ N, and $L_{C3} = 60$ N (Figure 5). From a qualitative point of view, the compound W100/AISI D2 exhibits an improved adhesion strength to the compound W75/AISI D2 because there are larger delaminated areas at critical load $L_{C1}$. However, the critical loads of the compound Mo100/AISI D2 were determined to be $L_{C1} = 30$ N, $L_{C2} = 60$ N, and $L_{C3} = 90$ N, and the critical loads of the compound Mo75/AISI D2 were determined to be $L_{C1} = 20$ N, $L_{C2} = 30$ N, and $L_{C3} = 70$ N. They were presented in previous publications [10,11].

Based on the results of the Rockwell and scratch tests, the compounds Mo100/AISI D2 and Mo75/AISI D2 exhibit significantly improved adhesion strength between coating and substrate in comparison to the compounds incorporated with W and S. In addition, an increase in the adhesion strength with decreasing bias voltage $U_{Bias}$ was observed.
3.3. Tribological Behavior

To investigate the tribological behavior of the deposited specimens, PoD and PoC tests were performed under dry sliding conditions. In addition, the uncoated cold work steel AISI D2 was tested as reference. The uncoated and unhardened counterpart material AISI 5115 was chosen because this material is used as typical semifinished products in cold forming. Figure 6a shows the coefficient of friction (CoF) of W100, W75, Mo100, and Mo75, which were deposited on the substrate AISI D2, as well as the uncoated reference. The reference was prior to testing in the same condition as the substrates before coating application.

Based on the results, all four coatings systems reveal significantly lower CoF compared with the uncoated reference AISI D2 which has a CoF ≈ 0.75. Furthermore, a different contribution of the coating systems in reduction of friction can be observed. Under the same conditions, the lowest CoF exhibits Mo75 with CoF ≈ 0.17 and Mo100 with CoF ≈ 0.34. In contrast, the coatings W100 and W75 led to a lower friction reduction with CoF ≈ 0.41 and CoF ≈ 0.45, respectively. In addition, there is a trend that the CoF is decreasing with decreasing bias voltage $U_{\text{Bias}}$. This can be explained by the increased sulfur content of the coatings deposited with lower bias voltage (Table 3), which most probably leads to increased TMD reaction layer formation under tribological stress. This phenomena were previously analyzed by Raman spectroscopy.$^{[10,11]}$ The analyses of the depth profiles orthogonal to the wear tracks on the basis of ten averaged surface profiles each using CLSM reveal that all coated samples and the reference AISI D2 uncoated exhibit low, not completely covering adhesive wear of the counterpart material (Figure 6b–d). The adhesive buildup on the reference's wear track amounts to $h \approx 1.3$ μm. The specimen Mo100 shows the lowest height of adhesives with $h \approx 0.3$ μm. The evaluation of the counterpart wear shows that the pin that ran against the uncoated reference surface exhibits the highest wear coefficient with $k = 325 \times 10^3 \mu m^3$ Nm$^{-1}$. The wear coefficients of the pins, which were tested against the coated samples W100 and W75, show lower abrasive wear with $k = 115 \times 10^3 \mu m^3$ Nm$^{-1}$ and $k = 121 \times 10^3 \mu m^3$ Nm$^{-1}$, respectively. The lowest counterbody wear was determined after the test against Mo100 and Mo75 with $k = 92 \times 10^3 \mu m^3$ Nm$^{-1}$ and $k = 67 \times 10^3 \mu m^3$ Nm$^{-1}$. As a result of the significantly lower wear coefficients of the counterparts running against the coated specimens, it can be concluded that self-lubricating tool coatings provide workpieces with improved surface finishes compared with uncoated tools.

In addition to the PoD tests, PoC tests were performed to simulate an open tribological system as it is present in cold massive full forward extrusion. The coated pins W100 and Mo100 were examined as each has the highest adhesion strength between coating and substrate. In addition, an AISI D2 uncoated pin as reference was tested. Figure 7 shows the apparent CoF* over the distance because the high normal forces of $F_N = 2600$ N lead to a plastic deformation of the cylinder.
Figure 6. a) Coefficient of friction CoF of the reference uncoated AISI D2 and coated specimens W100, W75, Mo100 and Mo75 against AISI 5115 using Pin-on-Disc tribometer and b) depth profiles orthogonal to the wear tracks of AISI D2, c) W100, and d) Mo100.

Figure 7. Apparent coefficient of friction CoF* of the reference AISI D2 uncoated and coated specimens W100 and Mo100 against AISI 5115 using PoC tribometer.

Figure 8. a) CLSM images and b) 3D micrographs of the AISI D2 uncoated pin and W100 as well as Mo100 coated pins tested in PoC tribometer.
Due to the self-lubricating hard coatings W100 and Mo100, a significant friction reduction was achieved. Both W100-pin and Mo100-pin exhibit low CoF* ≈ 0.1. This corresponds to a friction reduction by ΔCoF* ≈ −80%.

The wear analysis was performed using CLSM surface micrographs (Figure 8a) and 3D images (Figure 8b), to highlight the wear. The arrow indicates the direction of the relative movement of the pins. The curvature of the pin contours was corrected by software to improve the visibility of the 3D images.

Here, it should be mentioned that the correction of the round contour of Mo100 pin shows slight inaccuracies, which can be seen from the fact that the areas which were not in tribological contact do not exhibit a homogeneous color. The main wear mechanisms of the pins are a superposition of adhesive and abrasive wear phenomena. Especially, the AISI D2 uncoated pin exhibits strong cold welds up to a height of h ≈ 400 μm and partly abrasive wear. In contrast, the coated pins W100 and Mo100 have a high resistance to adhesive and abrasive wear. The maximum height of adhesive wear amounts to h ≈ 10 μm and h ≈ 20 μm. The PoC investigations reveal that both self-lubricating hard coatings have led to a significant reduction in friction and wear under dry test conditions at high loads.

4. Conclusion
In this work, self-lubricating hard coatings based on (Cr,Al)N, which were modified with W and S as well as Mo and S with varying bias voltages, were successfully deposited and characterized. To identify which incorporation elements are more suitable for the application of dry cold forming of steel, the mechanical properties, the adhesion strength between coating and substrate and tribological model tests were performed. Despite the high aspect ratios, the inner flanks of the forming dies were deposited with all four (Cr,Al)N + X:S coating systems: W100, W75, Mo100, and Mo75. Those exhibit good mechanical properties, in particular, the coatings deposited with UBias = 100 V. The coating systems incorporated with Mo and S exhibit significantly improved adhesion between coating and substrate compared with the W and S modified systems. The PoD tests show that the (Cr,Al)N + Mo:S coatings led to the lowest coefficient of friction. In the open tribological system, the coatings W100 and Mo100 lead to a significant friction reduction of ΔCoF* ≈ −80% compared with the AISI D2 uncoated pin while maintaining wear protection. Overall, the coating system Mo100 offers the highest potential for cold forming of steel, as it exhibits excellent adhesion to the substrate, considerable friction reduction, and high wear resistance.

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Conflict of Interest
The authors declare no conflict of interest.

Keywords
dry metal forming, high-power pulsed magnetron sputtering, physical vapor deposition, self-lubricating, tool coatings, tribology, wear

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