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Development, characterization and testing of tungsten doped DLC coatings for dry rotary swaging

Henning Hasselbruch[1], Marius Herrmann[2], Andreas Mehner[1], Hans-Werner Zoch[1], and Bernd Kuhfuss[2]

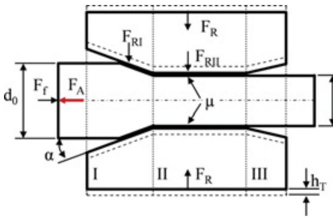
[1] IWT, Foundation Institute of Material Science, Surface Engineering, 28359 Bremen, Germany
[2] Bime, Bremen Institute for Mechanical Engineering, University of Bremen, 28359 Bremen, Germany

Abstract. The extensive use of lubricant during rotary swaging is particularly required for a good surface finish of the work piece and the reduction of tool wear. Abandonment of lubricant would improve the ecological process-balance and could also accelerate for further work piece refinements. Also cleaning of the manufactured components becomes obsolete. Thus, a dry machining is highly innovative, consequently new strategies to substitute the lubricant functions become necessary. To encounter the changed tribological conditions due to dry rotary swaging, low friction, tungsten doped, hard DLC coatings and structured surfaces are the most promising approaches. In this work the development of hard coating by means of reactive magnetron sputtering is presented, a promising layer variant is deposited on a set of tools and then tested and investigated in real use.

1. Introduction

Rotary swaging is an incremental cold metal forging process primarily used for manufacturing of rotationally symmetric automotive components such as axles or gear shafts in short cycle times. This non-cutting production process has several advantages as an increased static and dynamic strength of the work pieces due to strain hardening, an undisturbed fibre flow and an optimized utilization of the work piece material. Rotary swaging also allows manufacturing of hollow shafts with defined wall thicknesses. The infeed swaging variant, which is investigated in this study, is used for the reduction of the work piece diameter by the oscillating tool stroke h_T (see Fig. 1). The forging tools are arranged concentrically around the work piece, which is axially fed into the swaging unit with a feed force F_f. The axial reaction force F_A counteracts F_f which results from the radial force F_R respectively F_{RI} (I), F_{RII} (II), the tool angle α, the feed velocity v_f and in particular the frictional conditions μ (wet/dry) between the tools and the work piece material.

Conventional available rotary swaging tools are typically made of powder-metallurgical steels as ASP®2023. The reduction zone of these tools exhibits a rough surface by spray-coated tungsten carbide layers which increase the effective friction between the tools and the work piece. The increased friction causes a desired reduction of the axial reaction force F_A [1]. A disadvantage of the spray-coated tungsten carbide layers is their tendency of clogging with wear particles resulting in a loss of their tribological



α	= tool angle	F_{RII}	= radial force in zone II
d_0	= initial diameter	h_T	= tool stroke
d_1	= final diameter	μ	= friction
F_A	= axial reaction force	I	= reduction zone
F_f	= feed force	II	= calibration zone
F_R	= radial force	III	= exit zone
F_{RI}	= radial force in zone I		

Figure 1. Cross sectional view and nomenclature of the infeed rotary swaging process.

effectiveness. The related decrease of the surface quality of the work pieces can only be avoided by an extensive lubrication due to a hydrodynamic separation of tools and work piece.

Dry processing increases the thermo-mechanical stresses on the work piece and the tool. High process forces, contact pressures and high frictional shear stresses generate new surface areas on the work pieces which are free of protective oxide layers [2], leading to a significant increase of the abrasive and adhesive tool wear and a decrease of the work piece surface quality. Thus, dry rotary swaging with comparable robustness and work piece quality to the conventional lubricated process requires new strategies to substitute the versatile functions of the lubricant in rotary swaging. Two strategies to substitute the tribological functions of the lubricants were studied: Structuring and coating of the tool surfaces. Structuring of the tool surfaces in the reduction zone has a positive effect on the frictional behaviour as shown before [3] and will accelerate the discharge of wear particles from the forming contact area. The deposition of hard coatings on the total forming zone reduces the formation of wear particles due to adhesion and abrasion and will also protect the structured tools surfaces.

For lubricant free process conditions, hard coatings with low coefficients of friction show promising wear characteristics such as DLC (diamond like carbon) coatings [4]. DLC is the only coating material that can provide both high hardness and low friction. Because of their exceptional mechanical and tribological properties, these coatings are now used in a wide range of engineering applications to control friction and wear [5]. Very low coefficients of friction were achieved for DLC coatings with increased hydrogen content, a-C:H coatings (amorphous hydrogenated carbon), which have been studied by Erdemir et al. [6]. Friction is mainly controlled by abrasion, adhesion and shearing. The abrasive part of friction is due to plowing or scratching of surfaces by asperities or debris. The adhesive part of friction results from the formation of micro-junctions between the sliding counterfaces. Shearing results from plastic flow of interfacial materials (tribofilms) forming under sliding conditions [7]. Abrasive phenomena on a-C:H surfaces do not occur under most tribological contacts, because of their high hardness. Furthermore, a-C:H films show low tendency to adhesion against aluminium due to the saturation of carbon bonds by hydrogen or OH groups on the surface [2, 8]. The combination of extreme mechanical properties with weak surface interactions accounts for the low friction and high wear resistance of a-C:H films which therefore are seen to be the most promising variants [9]. A disadvantage is that a-C:H coatings show low bearing strength and overload protection [2, 10]. Consequently, the protection of the structured tool surfaces could be adversely affected due to the high dynamical loads.

In order to meet this challenge graded Cr/CrN_x/a-C:H:W coating systems were deposited on X153CrMoV12 (WKN 1.2379) tool steel substrates by reactive magnetron sputtering. The variants are shown in Fig. 2(a) and (b). Hard Cr/CrN_x-layers are used as adhesion promoter between substrate and the upper layers. A tungsten doped a-C:H interlayer (a-C:H:W) is used as an mediator between the adhesion and the top layer to further improve the fracture toughness [11, 12]. Both variants were tribologically analyzed, wherein the influence on mechanical properties of the deposition parameters was investigated for the Cr/CrN_x/a-C:H:W layer system. From these studies, a promising layer variant was selected and tools for dry rotary swaging are coated and tested in real use.

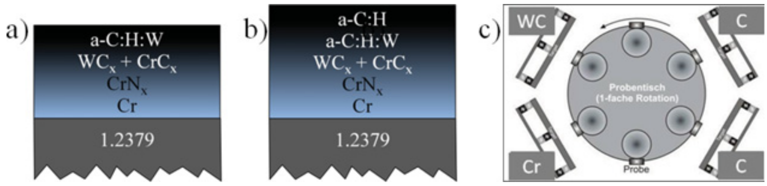


Figure 2. Investigated multilayer systems: a) Cr/CrN_x/a-C:H:W; b) Cr/CrN_x/a-C:H:W/a-C:H and c) selected target configuration for the depositing experiments.

2. Experimental procedures

The PVD coating experiments were carried out using an industrial CemeCon magnetron sputtering system CC800/9 SinOx. For the PVD deposition of both variants, the system was equipped with one tungsten-carbide-, one chromium and two graphite-targets (Fig. 1(c)). As substrates X153CrMoV12 (WKN 1.2379) hardened steel discs (62±2 HRC) were used. The discs were polished to an average surface roughness of Sa =∼ 4 nm and then cleaned in an Amsonic ECS40 ultrasonic cleaning system. The PVD process consists of three phases: heating, substrate etching and the coating process. The vacuum chamber was heated with a power of 15 kW for 1000 s to eliminate contaminations. For cleaning and activating of the substrates a plasma etching process for 1500 s at a bias voltage of −650 V under Ar and Kr atmosphere with a standard volume flow of $Q^n_{Ar/Kr} = 50\,cm^2/min$ was performed. The starting gas pressure was between 1 and 5 mPa for all processes. The power at the Cr- and C-targets was kept constant at 2 kW (4,2 Wcm^{-2}). The Ar- and Kr gas flow rates were kept constant at $300\,cm^2/min$ respectively $75\,cm^3/min$. The mechanical and tribological coating properties were investigated as a function of PVD deposition parameters as the WC-target power, the bias voltage and the acetylene gas flow (C_2H_2).

3. Results and discussion

3.1 Impact of PVD parameters on mechanical and tribological coating properties

On each specimen five scratch tests and six Rockwell C tests according to DIN EN 1073-3 and VDI 3198 were performed to determine the adhesion strength. Five ball grinding experiments were performed to determine the coating thickness. Figure 3 shows the critical load Lc2 and the adhesion class HF as a function of selected deposition parameters. Lc2 averaged about 40 N and the adhesion class was between HF1 and HF3 for all variants. A reduction of the WC-target power leads to an increase of the adhesion strength. Especially at 0.8 kW a significant increase to 57 N of Lc2 was observed. The reduction of the bias voltage from −150 V to −75 V leads to an increase of the adhesion strength. Variation of the acetylene flow Q^n_{C2H2} showed no clear correlation. The coating thickness was between 1.9 μm and 2.8 μm for all variants. While the thickness increased linearly with increasing WC-target power, no significant influence of Q^n_{C2H2} and bias voltage was observed.

The determination of the indentation hardness H_{IT} and the elastic indentation modulus E_{IT} were carried out in accordance to DIN EN ISO 14577.25 indentation tests were performed on each specimen with a maximum penetration force of 10 mN using the micro hardness measurement instrument Fischerscope H100C. Figure 4 shows that H_{IT} was between 15 GPa and 20 GPa and E_{IT} between 150 GPa and 230 GPa depending on the PVD deposition parameters. H_{IT} decreased when increasing $P_{WC\text{-}Target}$ from 0.6 kW to 1.2 kW, at 2 kW H_{IT} increased to 23 GPa. A slight increase of E_{IT} with increasing WC-target power was found. H_{IT} and E_{IT} increased with rising bias voltage (Fig. 4b) and both decreased with rising acetylene flow Q^n_{C2H2} (Fig. 4c).

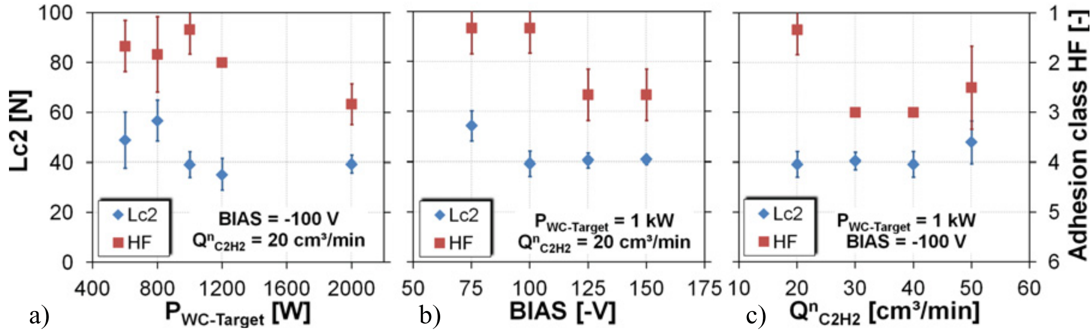


Figure 3. Measured critical load Lc2 (scratch test) and adhesion class HF (Rockwell-C test) depending on a) the WC-target power; b) the bias voltage and c) the acetylene gas flow rate.

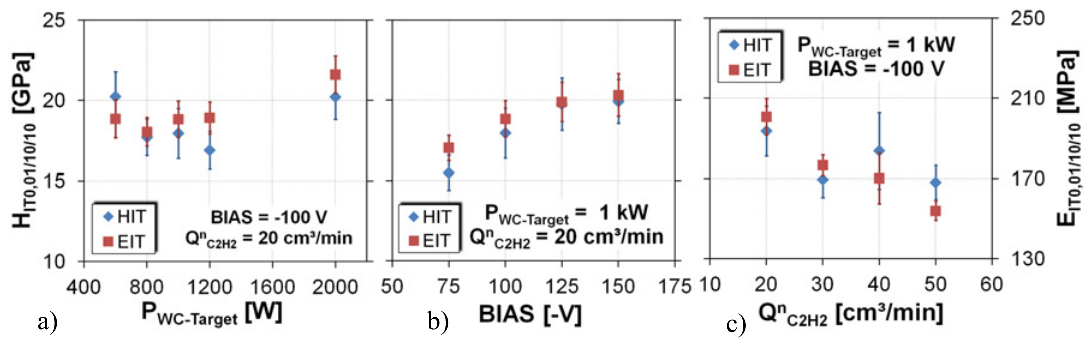


Figure 4. Indentation hardness H_{IT} and elastic indentation modulus E_{IT} ($F_{max} = 10$ mN, 10 s of loading, holding and unloading time) depending on a) the WC-target power; b) the bias voltage and c) the acetylene gas flow rate.

Dry pin-on-disk tribometer tests on uncoated and coated X153CrMoV12 steel disks were carried out against aluminum AlMgSi0.5 (EN-AW 6060) pins using a Wazau TRM 100 tribometer. The wear coefficients of the aluminum were determined by measuring the diameter of the pin wear scars with an optical microscope after three hours of testing at 1 N normal force and a sliding velocity of 0.25 m/s (see Fig. 5(a)). To determine the coefficient of friction the normal force was increased to 5 N and the duration was one hour at the same sliding velocity (see Fig. 5(b)). The evaluation of the wear scars shows that both coatings reduce the wear coefficients by at least two orders of magnitude for dry sliding. The tungsten free a-C:H top layer showed a lower wear coefficient (Fig. 5a) and a lower mean coefficient of friction of $\mu_{a\text{-}C:H/Al} = 0.25 \pm 0.05$ compared with the tungsten doped a-C:H:W coating $\mu_{a\text{-}C:H:W/Al} = 0.43 \pm 0.06$ (Fig. 5b). Figure 5c shows the wear trenches in the coatings using a Sensofar confocal microscope Plu2300. The width of the a-C:H wear track is smaller by a factor of two compared with the wear track of the a-C:H:W coating (see Fig. 5(c)).

3.2 Application test with coated rotary swaging tools

An application test with coated rotary swaging tools was performed. The recorded tracking error and the surface quality of rotary swaged AlMgSi0.5 tubes (EN-AW 6060) were measured for processing with and without lubricant using three different tools: A a-C:H coated tool (Fig. 6(a)), a plain tool (Fig. 6(b)) and a conventional tool spray-coated with a rough tungsten carbide layer (Fig. 6(c)). For all experiments

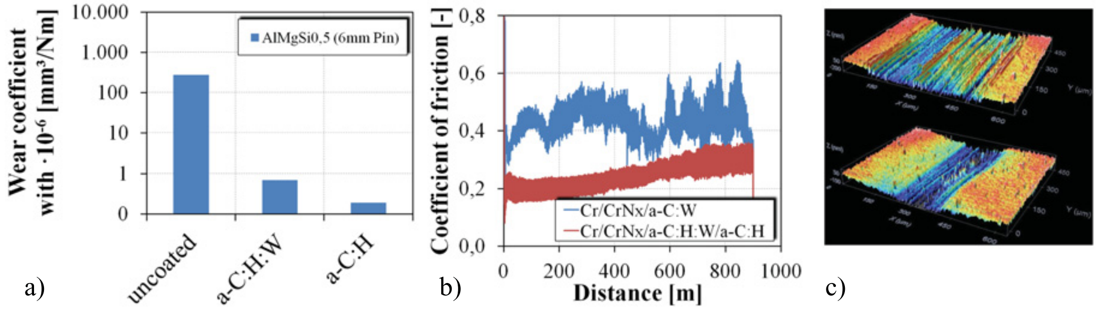


Figure 5. a) Wear coefficient against EN-AW 6060 pins: 1 N, 3 h, 0,25 m/s; b) curve characteristic of a-C:H:W and a-C:H functional layers: 5 N, 1 h, 0,25 m/s and c) images of the wear tracks: Cr/CrN$_x$/a-C:H:W at the top and Cr/CrN$_x$/a-C:H:W/a-C:H at the bottom.

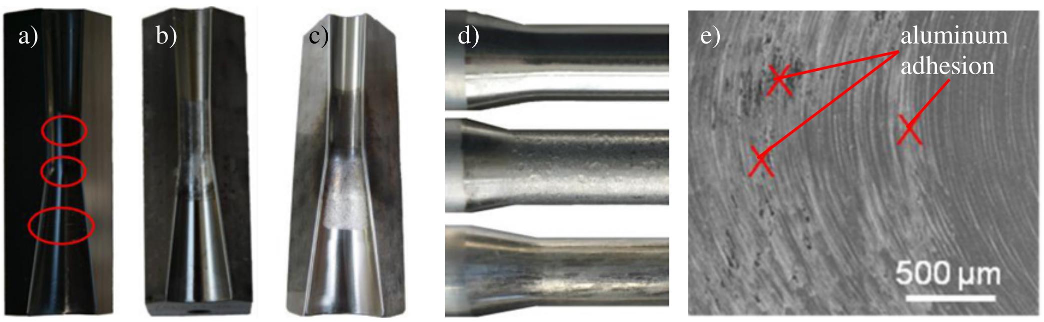


Figure 6. Tools and work pieces after forming a) coated tool; b) plain tool; c) conventional tool (with surface wrinkling of tungsten carbide); d) work pieces of aluminium, formed wet with plain tools (top), formed dry with plain tools (middle) and formed dry with coated tools (down) and e) SEM image of the reduction zone (I) with aluminium adhesion of a coated tool.

the tool geometry was the same (e.g. final diameter $d_1 = 15$ mm) as well as the process settings with the exception of four different feed velocities. The experiments were executed with a Felss swaging unit HE32. The feeding unit was implemented by a linear direct drive. For rotary swaging without lubricant the tools were cleaned each time before the process was started.

Rotary swaging with lubricant worked with all three tools. But, rotary swaging without lubricant was not practicable with the plain and the conventional tools. The surface quality of the work piece was poor (compare Fig. 6d) (top) and Fig. 6d) (middle)). A lot of aluminum particles adhere on the tool surface due to cold welding. Whereas the forming with coated tools was feasible with barely cold welding and the surface quality of the work pieces was clearly better (Fig. 6d) (down)).

The tracking error of the linear direct drive was measured in order to find stable process conditions. Therefore the mean of the maximal value per stroke was calculated. The tracking error was lower for all feed velocities for rotary swaging without lubricant (see Fig. 7). The increase with increasing velocity is due to the speed-dependent tracking error. The theoretical tracking error is sketch in. For the plain tool rotary swaging without lubricant was only done for one feed velocity and not at all with the conventional tools. The tracking error for the forming with lubricant and coated tools is greatest due to the lowest friction value closely followed by the tracking error of the forming with plain tools. For the forming with the conventional tools with the higher friction value due to the surface wrinkling the tracking error is almost as small as the tracking error for the forming with coated tools and without lubricant.

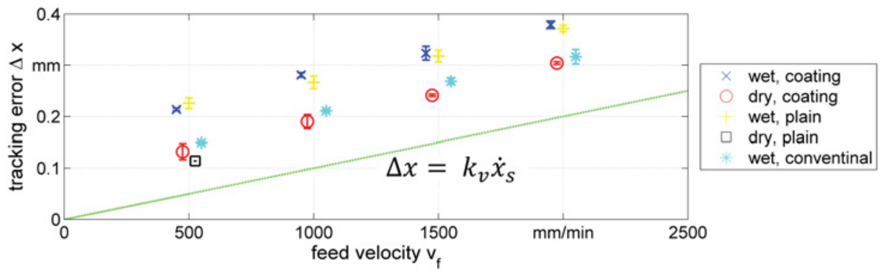


Figure 7. Tracking error for different feed velocities with (wet) and without (dry) lubricant.

After the forming tests, three critical areas on the coated tools were examined by scanning electron microscopy (SEM) (see Fig. 6a) red circled areas). In these areas, no coating failure could be observed. However, only small amounts of aluminium adhesion by means of EDX analyzes could be detected. This adhesion primarily occurs along the orientation of the hard-milling grooves (see Fig. 6d)).

4. Conclusion and outlook

PVD Cr/CrN_x/a-C:H:W coating experiments on hardened X153CrMoV12 tool steel specimens were carried out by reactive magnetron sputtering. The influence of several PVD process parameters on the mechanical properties of the coatings were investigated in order to find coating systems with optimized tribological properties. Pin-on-disk tests were performed on a-C:H:W and a-C:H variants and compared to uncoated samples in dry sliding contact.

In a first step, the mechanical coating properties were studied in the range of the selected deposition parameters for the Cr/CrN_x/a-C:H:W variant. Based on the tribological experiments the Cr/CrN_x/a-C:H:W/a-C:H coating variant shows the slightest sign of wear in dry sliding contact. For a first experimental investigation in real use, tools were coated with the second variant. The PVD coating parameters of this variant were $P_{WC\text{-}Target} = 1\,kW$, Bias voltage $= -100\,V$ and $Q^n_{C2H2} = 20\,cm^2/min$, because of promising mechanical properties and adhesion strength.

Wet and dry forming tests were carried out with uncoated and coated tools. No coating failure was observed. Due to the dry experiments, it was demonstrated that coated tools improve the work piece quality. The aim for actual researches is the development of the Cr/CrN_x/a-C:H:W/a-C:H coating variant. To further improve the adhesion strength, various tungsten gradings at the CrN- and a-C:H-interface are currently investigated as well as a duplex treatment by previous nitriding the tool steel. Also the influence of the deposition parameters to the mechanical properties of a-C:H functional layer will be tested. Another important step is the testing of the fatigue properties. For this purpose, impact tests with WC-balls are carried out in order to develop an optimal coating system against sliding and impact wear. These studies are particularly necessary towards an optimal protection when combining with the structuring of the reduction zone. Physical and chemical investigations such as XPS and GDOES analyzes take place on all coating variants for a better understanding of the mechanical properties in correlation to the forming phases and tungsten concentrations. A comparison of the tracking error indicates that the required energy input for coated tools in dry contact is at the same level as using conventional tools with lubricants. Hence, coating of tools provides an important contribution towards dry rotary swaging.

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