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Wear of nanostructured composite tool coatings

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The lifetime of forming tools can be increased by surface functionalization using novel, nanostructured coatings. A special centre of focus of this is the tribological requirements on the coating. Within the framework of the BMBF project, the friction and wear behaviours of 3 newly developed nanostructured composite tool coatings: VAlN, VAlN/VCAlN and VAlN/VCAlN with a carbon-enriched top layer, were examined and compared to each other. Because a conventional wear test would have required a large number of tests (⩾10,000) with a concomitantly high consumption of sheet metal, the examinations were run in a model trial at an increased surface pressure of 150 MPa, to accelerate the wear of the tool. Wear analysis was carried out by considering the changes in topography and hardness of the tool surface.

1. Introduction

The focus of the project was to develop new tool coatings as a prerequisite for a secure production process of high production runs. The background to this is the increased forces required when forming high-tensile sheet metal materials. When configuring forming tools, this often means that only an optimized tool coating can ensure secure functionality [1–4]. The coating is intended to reduce the adhesive and abrasive wear and in some cases to reduce the amount of lubricant and form an effective oxidation protection [5]. PVD (physical vapour deposition) and CVD (chemical vapour deposition) wear-protection layers provide extremely adhesive hard material layers (nitride or carbide of Ti, Cr, Al and Zr) that meet all of the wear-protection requirements: high rate of hardness (2000–4000 HV0.05), low frictional coefficients and high oxidation-resistance (up to around 900 °C) [6,7].

Resistance to wear, and therefore the lifetime of forming tools, can be further increased by surface functionalization using novel, multifunctional coatings. It is well known that many carbides and nitrides of translation metals in group IV–VI combine good surface properties [8]. Attempting to create new metastable materials in the form of nanoscale function coatings is driven by the possible combination of excellent materials properties [9]. The nanolaminate design of the multifunctional coatings increases toughness and crack meandering, and a variable proportion of carbon improves targeted adjustment of the friction coefficient.

2. Nanostructured composite coatings

Within the framework of the above-mentioned BMBF project, new, multifunctional tool coatings for sheet forming of high-tensile sheet metal materials were developed at the Institute for Material Research I (IMF I), Karlsruhe Institute of Technology, based on amorphous carbon [10] and carbon-based nanostructured composite layers. Amorphous, metal doped hydrogenated carbon layers are particularly suited for wear protection, especially due to their low tolerance to cold fusings [11]. They also aid in reducing lubrication requirement of, e.g. sheet steel coated by hot-dipping. Carbon-based nanostructured composite layers are composed of nanocrystalline binary, ternary or quaternary metastable hard material nanocrystals such as TiC, TiAlN or (Ti,Al) (C,N) that can ensure targeted tribological adjustment by varying the proportions in volume of crystalline and amorphous phases.

The coating selection for the project was guided by a thermodynamic assessment, which found that a metastable solid solution in both the VN–AlN as well as VC–AlN system would have to be synthesized more easily than in the established TIN–AlN system. During the interaction, parameter ε in the quasi-binary system TiN–AlN with 21 kJ/mol can be estimated; the VC–AlN system reaches one stable, low value of 16 kJ/mol. Furthermore, the critical separation of the TiN–AlN system is at 1240 K, while it reaches 960 K for VC–AlN.

At IMF I [10], a VAlN layer, a VAlN/VCAlN double layer and a VAlN/VCAlN triple layer with a top layer of excess carbon were developed in laboratory scale using high-frequency magnetron sputtering (a Leybold Z550 system) and then applied at the Technology Centre for Surface Engineering, Rheinbreitbach GmbH (TZO), on the IFU modelling tools (Fig. 1) in a CC800/8 type coating

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system from CemeCon [12]. All coating series were produced with a layer thickness of about 2–3 μm. A schematic representation of the layer configuration of the newly-developed tool coatings is shown in Fig. 1.

To deposit the binary coatings, one pair of targets (high purity, 99.9%) was used. Ternary VAlN coatings were deposited by sputtering from the so-called VAl-plug targets (V targets with 20 Al plugs, V purity 99.9%, Al purity 99.95%, target geometry patented by CemeCon AG). Due to the character of the coating system, classical one-by-one trial and error approach was used. The four process steps for the CemeCon vacuum deposition system after the evacuation of the chamber are a heating, an etching, a coating and a cooling-down procedure. The first step, heating, is a very important prestep. By opening the chamber for loading the deposition system, all surfaces are contaminated with adsorbed water molecules. These molecules are disadvantageous for adhesive properties of the coatings and can be removed by a heating procedure. The heating procedure, like all other steps, is an adjustable process step. The coating system allows heating power variability from 500 W to 12 kW (the substrate temperature during deposition averages 350 °C, measured by a bimetal drag indicator thermometer). For industrial applications, typically a power of 3 kW is used in order to achieve the preferred temperatures in a short time. In order to remove the oxide layers after the heating period, the surface of the samples has been etched by means of Ar^+-ion-bombardment. Typically used bias voltage for this step was −70 V, normally increased up to −200 V, and applied substrate r.f. power bias 1.500 W. These parameters were held constant for all the coatings. VN, AlN and VAlN coating series were performed with different bias voltages, varying from −80 to −200 V in 30 V steps. The deposition pressure was varied by changing the Ar/N_2 flow ratio and the quantity of the process gases (total pressure during coating deposition by all coatings was in the range of 300–900 MPa).

The scaled layer has a crystal size of 4–5 nm, determined by X-ray powder diffactrometry, and harnesses of up to approximately 4000 HV0.001, as well as good adhesion for the tools.

3. Surface examinations of the coated tools

Before commencing the wear examinations at the IFU, the tool surface topography was determined for each type of coating and the results were compared. The topographies were determined using a *μsurf mobile* optical 3D measuring system (manufactured by Nanofocus). The measuring system *μsurf mobile* offers a nanometer precision resolution. This is based on confocal Multi-Pinhole-Technology in combination with the precise piezo-module. Rough surfaces and structures with steep flank angles can be captured reliably and even strongly reflecting can be transformed into measurement data error-free. The objective lens used offers individual measurement field sizes between $1.6 \times 1.6\ \mathrm{mm}^2$ and $260 \times 260\ \mu\mathrm{m}^2$ with freely selectable vertical resolution. After each measurement, real 3D data are available, and μsurf analysis also offers numerous other functions, such as volume determination, calculation of isotropy or particle analysis.

All measures of surfaces were made with an optical modus 320 S: measuring field 320 μm × 320 μm, enlargement 50, working distance 1 mm, resolution in *z*-direction 2 nm, and resolution in *x*-, *y*-direction 0.7 μm.

The tool surface contains material and holes (recesses). The scores from the tool material (substrate) can be detected during a visual analysis of 3D surface views of coated tool surfaces. The VAlN (single coating) layer is distributed in waves along the scores. The double layer and especially the triple layer partially close between the score spacing, with formation of a new plateau on the tool surface (Figs. 2–4). This effect can be seen when comparing the surface profiles, whereby the VAIN single layer shows the largest surface of the recess (holes), at 36.5 $\mu\mathrm{m}^2$ (Fig. 2).

The double and triple layers thereby correspondingly cover and reduce the area of the recess to 16.7 and 29.2 μm (Figs. 3 and 4 respectively). The area of the recess from the 2D calculation correlates to the 3D recess empty volume of the surface and characterizes the absorptive capacity of the tool surface for lubricants. This absorptive capacity is the greatest for the single-layer although from all three examined layers, this has the smallest mean arithmetical height of Sa = 0.15 μm, thereby nearing the mean height of the substrate (Sa = 0.12–0.13 μm).

The isotropy of the surface structure of coated surfaces is of great interest. This isotropy characterizes the relation between the texture and the appearance of the surface. If the value is near 100% the surface is isotropic, i.e. exhibits the same characteristics in all directions and has no preferred direction. If the value is near to 0% then the surface is anisotropic, i.e. exhibits an aligned or periodic structure. During deep drawing, where various drawing directions occur relative to the sheet rolling direction, isotropy is

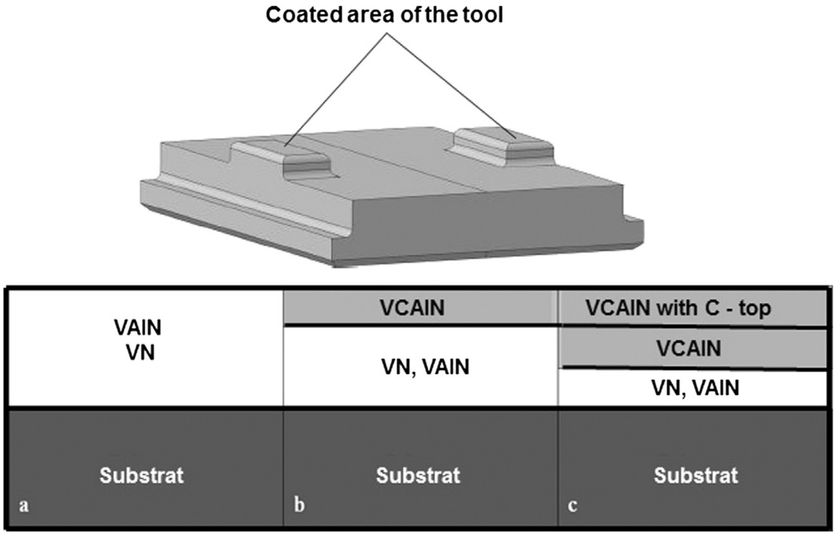

Fig. 1. Schematic representation of the modelling tool and the layer configuration of newly-developed tool coatings: vanadium aluminum nitride (VAlN), vanadium carbide aluminum nitride (VCAlN), vanadium nitride (VN), and carbon (C) [TZO].