Vol. 34, No 2 (2012) 51-56

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Wear Behavior of PVD-Coatings

M. Merklein[a], T. Schrader[a], U. Engel[a]

[a]*Chair of Manufacturing Technology, Department of Mechanical Engineering, Friedrich-Alexander-University Erlangen-Nuremberg, Germany*

Keywords:

PVD
Coatings
Wear

Corresponding author:

M. Merklein
Chair of Manufacturing Technology,
Department of Mechanical Engineering,
Friedrich-Alexander - University
Erlangen-Nuremberg, Germany
E-mail: m.merklein@lft.uni-erlangen.de

ABSTRACT

In cold forging high tribological loads often lead to premature tool failure. If the cause of failure is wear, an extension of tool life can be achieved by applying PVD coatings. According to the different load cases appearing in cold forging processes, the development of a great variety of coatings with different properties is crucial for adjusting their properties to the plurality of applications. In order to investigate the developed coatings concerning their suitability for different processes, a sufficient characterization of the coatings is required. In this paper six different PVD coatings are investigated in the three-ball-on-disc test giving a basic impression towards wear behavior of the coatings and predominant wear mechanisms.

1. INTRODUCTION

Current trends in cold forging industry are mainly driven by the requirements of automotive industry. The demand for weight reduction is motivated by the call for reduction of fuel consumption and CO_2 emission. Lightweight design is either achieved by using high strength materials or by part integration leading to a reduction of process steps and of assembled parts [1]. However, the use of high strength materials and the forming of integrated parts with complex geometries lead to high tribological loads on the tools and in many cases to early tool failure [2, 3]. A second trend caused by the demand for cost reduction and increasing quality of the components at the same time is the near-net-shape manufacturing implying the production from the initial workpiece to the final product reducing the need of subsequent machining [4]. High accuracy of the product regarding geometry and surface claims a high surface quality of the tool assured over the whole tool life. The increasing tool loads on the one hand and the demand for high surface quality of the tool on the other hand lead to the application of PVD-coatings on tools in order to reduce wear, to extend tool life and to increase surface quality of the product [5]. In industry there is a diversity of different load cases due to the plurality of produced parts. Depending on the industrial load case, different aspects are decisive for wear. Hence, the development of a great variety of coatings is crucial for adjusting their properties to the plurality of applications [6]. In order to investigate the developed coatings concerning their suitability for different processes, a sufficient characterization of the coatings is required. In comparison to material properties tribological variables like wear depend on a variety of factors and are difficult to determine. Since in many cases the cause of tool failure is wear, the investigation of wear behavior of the coatings is crucial. Methods for wear investigations like the pin-on-disk tribometer [7] and the calotest [8] can not fully reflect the real conditions of cold forging processes. Nevertheless, the tests give the opportunity for basic investigations on the tribological behavior of coatings. In comparison to tests, which are carried out under conditions of real processes, the experimental setup and the preparation of the specimens are relatively simple. Thus, it is possible to test various coatings in a relatively short time. For coatings showing potentially advantageous wear behavior in the basic tests further investigations in the upsetting-sliding test [9] or the combined punching-forward extrusion test [10] can be carried out under process relevant conditions. Within the scope of this study six different PVD-coatings are investigated which are actually applied in cold forging or being in development. The wear behavior of the coatings is tested in a three-ball-on-disc tribometer [11]. The occurring wear is investigated by confocal and scanning electron microscopy in order to give a first impression of the wear mechanisms and wear initiation of the coatings.

2. EXPERIMENTAL SETUP

2.1 Three-ball-on-disc test

For wear investigations the three-ball-on-disc test is used which is a modified version of the well known pin-on-disc test. The three-ball-on-disc test is chosen in order to avoid tipping of the pin on the coated specimen [11]. The tests are carried out on a WAZAU tribometer TRM 1000. In the setup of the test three balls of the bearing steel 1.3505 rotate on a planar coated specimen with an oscillation of 90° (Fig. 1).

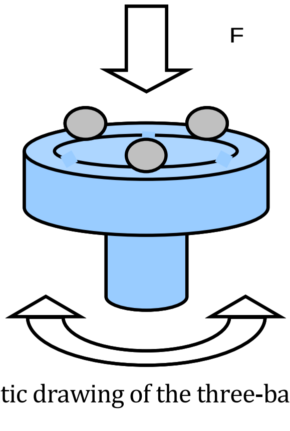

Fig. 1. Schematic drawing of the three-ball-on-disc test.

For the specimens with a diameter and height of 30 mm and 5 mm respectively the common high speed steel 1.3343 is chosen which is often used for cold forging tools. Due to elastic behavior of the materials, the load on the specimens applied by the balls is characterized by Hertzian stress at the beginning of the test leading to high tribological loads and the occurrence of wear in a relatively short time [12]. The load on the specimens is calculated as follows.

$$\sigma_{max} = \frac{1}{\pi} \cdot \sqrt[3]{\frac{1.5 \cdot F\,E^2}{r^2\,(1-\nu^2)^2}} \qquad (1)$$

Here, the tribological load is characterized by the maximum stress σ_{max} being located in the center of the interface between specimens and balls. On the three balls a normal force of $F = 60$ N is applied. The maximum stress is calculated using the Young's modulus and Poisson's ratio of the balls of $E = 210$ kN/mm^2 and $\nu = 0.3$ respectively in lack of the values for the coatings. The radius of the balls is $r = 2.39$ mm. With the given values the maximum stress is calculated to be σ_{max} = 2081 N/mm^2 resulting in high tribological loads on the coated specimens for an ideal Hertzian contact at the beginning of the test. On the one hand the tribological load decreases with an increasing number of cycles due to the enlargement of the interface between specimens and balls caused by wear. On the other hand the tribological load increases with number of cycles due to the increasing roughness of the surfaces of the contact bodies. The high tribological load caused by Hertzian stress is additionally intensified by testing without lubricant leading to early wear occurrence. Hence, the three resulting wear traces can already be investigated after 1000 cycles with one cycle meaning a rotation of the specimen of 90° and a rotation backwards to its initial position. With a rotation diameter of 25 mm the sliding path for one trace and one cycle adds up to 39.27 mm. For each coating described in the following paragraph three specimens have been investigated.

2.2 Coatings

Compared to other coating processes like the CVD-process, the PVD-process is advantageous because of its low process temperatures, which do not affect the microstructure and hardness of the substrate [13]. Thus, two types of monolayer PVD-coatings based on TiN and TiAlN respectively, two types of multilayer PVD-coatings based on TiC and TiAlCN respectively, one nanolayer PVD-coating based on AlCrN and one nanostructure PVD-coating based on Si_3N_4/AlTiN are investigated, which have been chosen due to the basic characteristics like their structure, maximum working temperature and micro hardness given in Table 1.

Multilayer coatings consist of multiple individual layers. Having a simple structure two different individual layers with different properties are alternating. A more complex structure in combination with further individual layers is possible. Thus, multilayer coatings have a greater potential to be adjusted to an application than monolayer coatings. In addition, coatings with a multilayer structure can potentially reduce crack extension, since initiated cracks can be stopped at the transitions of the individual layers. In case the thickness of the individual layers is reduced below 20 nm, the coating is called nanolayer or superlattice. Inducing stresses between the different lattice planes this coating structure leads to a further increase in hardness [6]. Another approach for PVD-coatings is the nanostructere coating or nanocomposite, which consists of a crystalline and an amorphous phase, showing properties of nanomaterials like superplastic behavior [6].

2.3 Wear analysis methods

For wear examination various methods come into consideration. The surfaces of the specimens have been investigated by confocal and scanning electron microscopy. For visualizing wear mechanisms images have been taken by the scanning electron microscope (SEM). Additionally, the topographies of the specimens have been investigated three-dimensionally by confocal microscopy. For the measurements an objective with a 10x magnification is used resulting in a measuring field of 1.6 mm x 1.6 mm. According to [14] and [15] the occurrence of wear is systematically attributed to the four wear mechanisms adhesion, abrasion, surface fatigue and tribochemical reaction. Depending on the load and the properties of the contact bodies one or several wear mechanisms are dominant. Though several methods for qualitative wear analysis by several types of microscopy are available, the possibilities of quantitative wear analysis are limited. The characterization of the occurred wear by traditional two-dimensional roughness parameters is limited due to the three-dimensional character of the wear debris. The three-dimensional roughness parameters developed for the functional characterization of the tribological behavior of sheet metals in [16] and [17] are not suitable because of the inhomogeneity of the weared surface. The deviation of the measured roughness of a wear trace for one single coating is too high to get reasonable results. Thus, for a quantitative wear analysis the occurred wear on the balls has been investigated by confocal microscopy. The volume of wear dissipated of the balls corresponds to the material adhered on the specimens, and thus can be taken as a measurement for adhesive wear. For a determination of the dissipated volume of the balls the diameters of the abraded surfaces of the balls has been measured by the confocal microscope. The diameters of the weared surfaces are measured five times for each ball. The volumes are calculated with the mean diameters for each coating.

Table 1. Basic characteristics of the considered coatings [1].

	TiN	TiAlN	TiAlCN	TiC	AlCrN	Si_3N_4/ AlTiN
structure	monolayer	monolayer	multilayer	multilayer	nanolayer	nano-structure
max. working temperature (°C)	500	750	800	450	900	900
micro hardness ($HV_{0.05}$)	2300 +/- 200	2800 +/- 300	3500 +/- 500	3700 +/- 200	3000 +/- 300	3500 +/- 500

3. CHARACTERIZATION OF THE COATINGS

For wear investigations the surface roughness plays a significant role. The initial surface roughness of the coated specimens for the considered coatings is given by the arithmetic mean roughness *R*a = 0.20+/-0.05 µm. The deviation is mainly caused by droplets generated in the coating process. The three dimensional measurements by confocal microscopy provide a detailed view of the resulting wear on the specimens. In order to indicate heightenings and cavities, roughness profiles are extracted. As can be seen in Figs. 2–6, the coatings reveal a different wear behavior on the specimens after 1000 cycles. Since the monolayer coatings TiN and TiAlN and the nanolayer coating AlCrN show similar wear behavior after 1000 cycles, wear and roughness profile of the specimen coated with TiAlN is shown in Fig. 2 representatively for the three coatings.

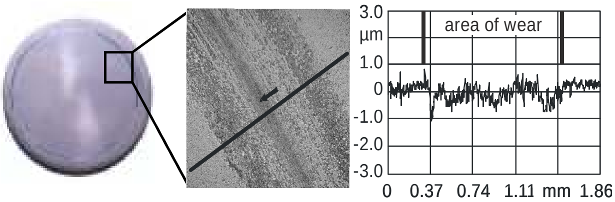

Fig. 2. Roughness profile of the wear trace on the TiAlN coated specimen after 1000 cycles.

The specimen coated with monolayer TiAlN shows grooves of wear, which reach depths up to 1 µm. With a coating thickness given by the coating company of more than 3 µm the substrate is not affected. The heightenings up to 0.5 µm result from adhered material. The occurrence of wear might be attributed to insufficient hardness of the three coatings (Table 1).

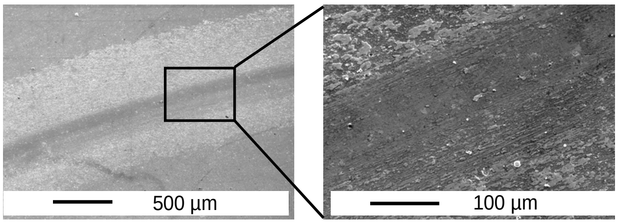

Fig. 3. Wear on the TiAlN coated specimen taken by SEM after 1000 cycles.

The investigations by SEM allow a detailed view on the occurred wear. In Fig. 3 grooves are visible on the TiAlN coated surface. On the roughened surface material of the balls adhered in a section of about 1 mm width (Fig. 2). The relatively large section of wear can be explained by the enlarged contact surface of the balls with a measured diameter of 1.1 +/- 0.1 mm after testing. Thus, for the coatings TiN, TiAlN and AlCrN the occurrence of wear is mainly caused by the wear mechanism adhesion.

Having a more detailed view with a 1000x magnification on the TiN coated surface sections are visible, which are typical for surface fatigue (Fig. 4). This kind of wear is caused by cyclic loading leading to the initiation of microcracks [14]. In contrast to multilayer coatings the crack is not potentially stopped at the transitions of next individual layers. The cyclic load induces growing of the crack and leading to chipping of the coated surface. Beside adhesion surface fatigue is dominant for the TiN coated surface.

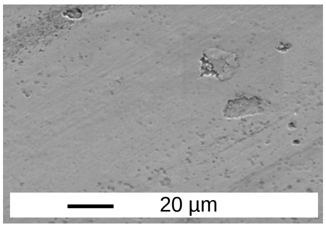

Fig. 4. Wear on the TiN coated specimen taken by SEM after 1000 cycles.

Since the multilayer coatings TiAlCN and TiC and the nanostructure coating Si_3N_4/AlTiN show similar wear behavior after 1000 cycles, wear and roughness profile of the specimen coated with TiC is shown in Fig. 5 representatively for the three coatings. In the section of contact droplets and asperities have been abraded. The area of wear for these coatings is smaller than for the coatings TiN, TiAlN and AlCrN. The averaged measured diameter of the contact surface of the balls results to 0.9 +/- 0.1 mm. Hence, less material adhered on the surfaces of the coatings TiAlCN, TiC and Si_3N_4/AlTiN.

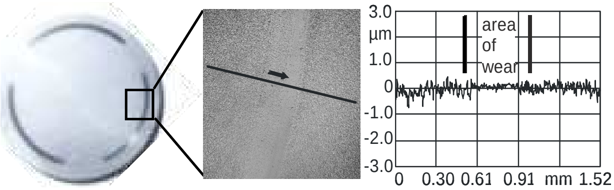

Fig. 5. Roughness profile of the wear trace on the TiC coated specimen after 1000 cycles.

Only small traces of wear like tiny pittings and adhesion are detectable (Fig. 5). The high wear resistance of the multilayer and nanostructure coatings might be attributed to their high hardness.

For a detailed view of the occurred wear the TiC coated specimens are investigated by SEM as well. Only sparse signs of wear grooves and adhered material are detectable (Fig. 6). The hardness of the coatings TiAlCN, TiC and Si_3N_4/AlTiN prevents the initiation of abrasive wear and surface cracking. Thus, the risk of adhesion on the roughened surface is reduced.

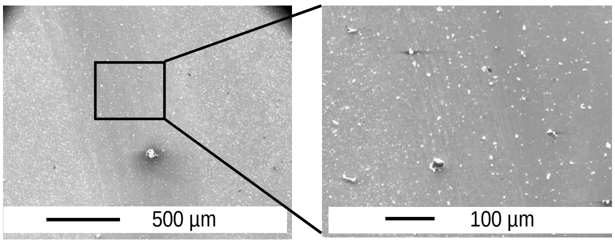

Fig. 6. Wear on the TiC coated specimen taken by SEM after 1000 cycles.

For a quantification of the adhered material the diameters of the flattened sections of the balls are measured and the dissipated volumes of the balls are determined. It should be noted, that deviations of the diameters result in high deviations of the volumes. The adhered wear volumes differ for the tested coatings (Fig. 7). The wear volume for the coatings TiAlCN, TiC and Si_3N_4/AlTiN is lower than for the coatings TiAlN and AlCrN. As stated above the high hardness prevents roughening of the surface leading to reduced occurrence of adhesion. The wear volume of the coating TiN compared to TiAlN and AlCrN is lower. Roughening of the TiN coated surface lead to less adhesion than for TiAlN and AlCrN. Beside adhesion the wear mechanism surface fatigue occurs on the TiN coated surface. Thus, beside hardness further factors like the stoichiometric composition of coatings influence their wear behavior.

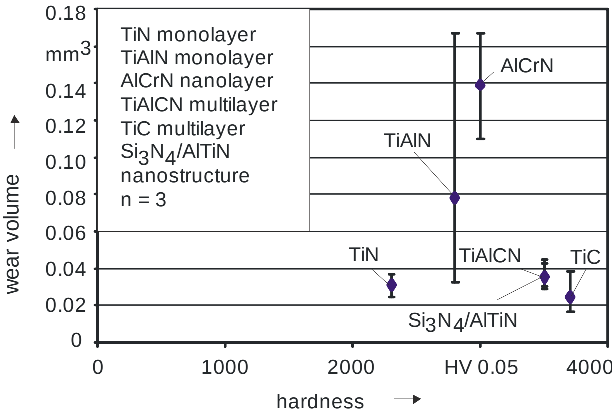

Fig. 7. Volume of wear in relation to the hardness of the coatings.

4. CONCLUSIONS

In cold forging processes PVD-coatings have the potential to prevent early tool failure caused by high tribological loads. A characterization of their tribological behavior is essential for investigating their suitability for different processes. With the three-ball-on-disc test it is possible to test various coatings regarding their basic wear behavior in a relatively short time. Within the scope of this paper two types of monolayer PVD-coatings based on TiN and TiAlN respectively, two types of multilayer PVD-coatings based on TiC and TiAlCN respectively, one nanolayer PVD-coating based on AlCrN and one nanostructure PVD-coating based on Si_3N_4/AlTiN have been investigated. The roughness profile of the coatings TiN, TiAlN and AlCrN show heightenings and cavaties with a height and depth respectively of 1 µm. On the surfaces of these coatings investigated by SEM wear grooves and large sections of adhered material are detectable. Furthermore, on the surface coated with TiN sections of surface fatigue are visible. The cyclic load causes initiation and growth of microcracks leading to chipping on the coated surface. In contrast the surfaces coated by TiC, TiAlCN and Si_3N_4/AlTiN reveal little signs of wear like tiny pittings and adhesion in few sections. Thus, the coatings TiAlCN, TiC and Si_3N_4/AlTiN reveal a higher wear resistance than the coatings TiN, TiAlN and AlCrN. Due to their higher hardness the occurrence of wear grooves on the coatings Si_3N_4/AlTiN, TiAlCN and TiC is decreased resulting in a reduced tendency for adhesion. Beside the qualitative investigations a quantitative characterization of the occurred wear has been carried out. The wear of the coatings is determined by measuring the mean volume dissipated of the balls. The wear volume of the coatings TiAlCN, TiC and Si_3N_4/AlTiN is lower than for the coatings TiAlN and AlCrN. The results of the qualitative analysis are confirmed by the quantitative characterization of wear. For the coating TiN the wear volume is lower than for the coatings TiAlN and AlCrN as well. In investigations by SEM chippings are detectable on the TiN coated surface potentially caused by microcracks. In case of the coating TiN surface fatigue occurs as a further predominant wear mechanism beside adhesion. Thus, beside hardness further factors like the stoichiometric composition of coatings influence their wear behavior. Testing with the three-ball-on-disc test has the potential for determination of the basic wear behavior of PVD-coatings in a relatively short time. The qualitative and quantitative investigations of the occurred wear give first impressions of wear initiation and wear mechanisms. Further investigations should focus on the characterization of wear behavior in wear tests carried out under conditions as they are common in cold forging processes.

Acknowledgement

The research work presented in this paper is supported by the Bavarian Research Foundation and industry within the joint research program ForLayer.

REFERENCES

[1] H.-W. Raedt, *Leichtbau durch Massivumformung*, VDI-Berichte Band 1766, Düsseldorf: VDI-Verlag, 2003.

[2] K. Lange, *Umformtechnik – Handbuch für Industrie und Wissenschaft*, Springer, Berlin, Vol. 1, 1984.

[3] U. Engel, *Beanspruchung und Beanspruchbarkeit von Werkzeugen der Massivumformung*, Meisenbach Verlag, Bamberg, 1996.

[4] D. Landgrebe, H.-W. Raedt, *(Near-) Netshape in der Massivumformung für den automobilen Leichtbau, (Near-) netshape technologies in bulk metal forming for lightweight automotive engineering*, *MEFORM*, 30.03-01.04.2005, Freiberg, Germany.

[5] C. Hinsel, *Ermüdungsbruchverhalten hartstoffbeschichteter Werkzeugstähle in der Kaltmassivumformung, Dissertation*, Universität Erlangen-Nürnberg, Bamberg: Meisenbach Verlag, 2000.

[6] K. Bobzin, E. Lugscheider, C. Pinero, *New PVD-coating concepts for highly stressed tools for environmentally compatible manufacturing processes*, Materialwissenschaft und Werkstofftechnik, Vol. 35, No. 10/11, pp. 851-857, 2004.

[7] DIN EN 1071-13, Hochleistungskeramik– *Verfahren zur Prüfung keramischer Schichten– Teil 13: Bestimmung der Verschleißrate mittels Stift-Scheibe-Prüfung*, Berlin: Beuth-Verlag, 2008.

[8] M. Eder, R. Bethke, *Präzisionsverschleißmessung an dünnen Schichten als Mittel zur Qualitätssicherung und Schichtcharakterisierung*, Materialwissenschaft und Werkstofftechnik, Vol. 31, No. 12, pp. 1056-1059, 2000.

[9] M. Dubar, A. Dubois, L. Dubar, *Wear analysis of tools in cold forging: PVD versus CVD TiN coatings*, Wear, Vol. 259, No. 7-12, pp. 1109-1116, 2005.

[10] T. Schrader, M. Merklein, U. Engel, *Qualification of a new test for wear investigation on coated tools*, in: Proceedings of the 4th International Conference on Tribology in Manufacturing Processes (ICTMP), 2010, Paris, France, pp. 303-312.

[11] ISO 20808, *Fine ceramics (advanced ceramics, advanced technical ceramics) – Determination of friction and wear characteristics of monolithic ceramics by ball-on-disc method*, Berlin: Beuth Verlag, 2004.

[12] W. Beitz, K.-H. Grote, *Dubbel Taschenbuch für den Maschinenbau*, Springer, Berlin, 2001.

[13] Eifeler Beschichtungscenter GmbH, *PVD-Beschichtung*, available at: www.eifeler.com, accessed: 23.05.2011.

[14] H. Czichos, K.-H. Habig, *Tribologie-Handbuch, Tribometrie, Tribomaterialien, Tribotechnik,* Wiesbaden: Vieweg+Teubner Verlag, Germany, 2010.

[15] K. Sommer, R. Heinz, J. Schöfer, *Verschleiß metallischer Werkstoffe: Erscheinungsformen sicher beurteilen*, Wiesbaden: Vieweg+Teubner Verlag, Germany, 2010.

[16] M. Pfestorf, U. Engel, M. Geiger, *3D-Surface Parameters and their Application on Deterministically Textured Sheet Metals*, International Journal of Machine Tools and Manufacture, Vol. 38, No. 5-6, pp. 607-614, 1998.

[17] U. Popp, T. Neudecker, U. Engel, M. Geiger, *Surface characterization with regard to the tribological behaviour of sheet metal in forming processes*, in: *Proceedings of the International Conference SheMet'99*, 27-28.09.1999, Erlangen, Germany, pp. 303-310.