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Original Research Article

Optimized plasma nitriding processes for efficient wear reduction of forging dies

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ABSTRACT

Plasma nitriding treatments are approved to reduce wear occurring in the field of hot forging applications. But there are demands for a further optimization of the processes in order to achieve adapted properties for differently loaded forging tools. This work presents the influence of main process parameters on the wear behavior of dies. The focused steel material of this work is DIN-X38CrMoV5-1 (1.2343), a standard hot forming tool steel. The influence of nitriding parameters like temperature, nitrogen flow and time on the nitriding depth, hardness and crack sensitivity has been investigated. Comparative application tests show the influence of different surface treatments on the wear behavior and lifetime of forging tools in an industrial environment.

1. Introduction

Simultaneously occurring high mechanical and thermal loads are leading to severe tool damage in the field of hot forging applications. Forging dies, commonly made of hot forming tool steels, have to be resistant against rough conditions. The cyclic contact to the preheated billets with temperatures above 1000 °C, hard particles like scale and oxides in combination with high pressure load are leading to heavy adhesive and abrasive wear. Alternating heat transfer by the preheated part and tool as well as spray cooling with water based lubricants can cause high internal stress, crack initiation and fracture of the forming die [3]. Fig. 1 illustrates the different stages of the forming process.

The rough process conditions caused by thermal and mechanical loads as well as thermal shock conditions are leading to crack initiation and crack growth. As a result extensive wear will be initiated by mechanical spalling of the tool surface.

In the past, hot forming tools have been improved by a variety of surface engineering processes, such as surface welding, thermal spraying, electro depositioning, diffusion treatments and combined techniques. By now, especially gas- or plasma-nitriding of the tool steel is very common to increase the lifetimes of hot forming tools. Nitriding can increase the surface hardness as well as the wear and corrosion resistance of forging dies [10]. The generation of inherent compression stress can reduce the tendency of crack formation and elevate the fatigue strength. Adversely the increase of hardness by nitriding comes along with a reduction of the tool edge layer ductility [1,6].

The use of PVD- and PACVD-coating like TiAlN, TiCN, TiBN, CrN or CrVN can improve the wear resistance of

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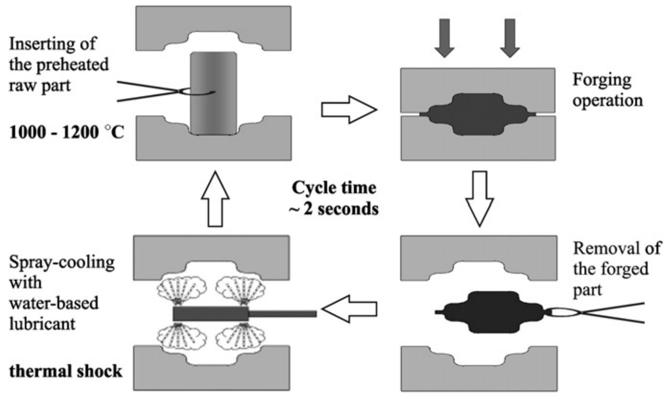

Fig. 1 – Principle of die-forging process.

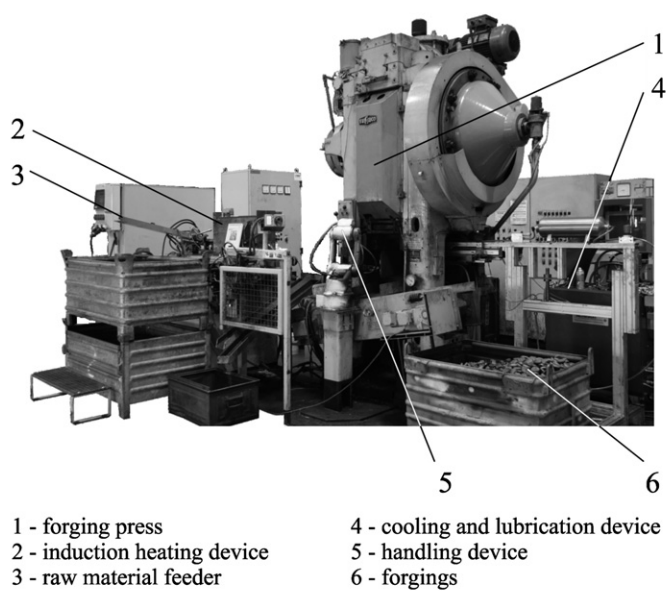

Fig. 2 – Automated forging line at IFUM for long term tests.

forging dies additionally [5]. Combination processes of plasma nitriding and additional coating (Duplex processes) for hot forming applications are described in the literature [4,7,8,11,12]. The hardened zone created during the plasma diffusion treatment offers mechanical support to the hard coatings, which enhances their load-bearing capacity. The danger of the so called eggshell-effect on soft substrates is reduced [2]. Nevertheless, coatings are not state-of-the art in forging industry. Since modern plasma treatments seem to be cost intensive compared to conventional methods like gas nitriding the advantages in means of an increased tool life or process optimization have to be clearly emphasized.

Analyses of different nitrided and coated forging tools in various production processes have shown crack formation as decisive factor of tool life [9,13].

The demand for short cycle times and the necessity of water based spray cooling cause severe thermo-shock conditions. After a few working strokes a crack network appears on the tool surface. The cracks act as starting points for destructive pitting, crevice corrosion, abrasive and adhesive wear. This behavior could not be affected by the different coatings and their influence on the tool life was negligible.

The objective of the present work is to improve the wear behavior of coated hot forming tools under thermo shock conditions by optimized plasma nitriding. This can be done by appropriate adaptation of the process parameters.

2. Experimental

Forging dies and testing samples were made of DIN-X38CrMoV5-1 (1.2343) hot forming tool steel with a composition of C=0.39%, Cr=5.30%, Mo=1.30%, and V=0.40%. This standard material in the hot forging industry was used for the specimens and manufactured tools for forging and industrial field tests. All specimens and tools were hardened to 48±2 HRC.

Nitriding and the characterization of the nitrided materials were conducted at the Fraunhofer Institute for Surface Engineering and Thin Films (IST) in Braunschweig, Germany. For the processes an industrial plasma diffusion chamber with unipolar pulse plasma supply was used. Nitrogen flow, nitriding time and substrate temperature were varied. Typical process parameters were: temperature 520/560 °C, treatment time 16 h, pressure 350 Pa, voltage 500 V, duty cycle (pulse duty factor) of $D=0.25$ and $D=0.17$ (i. e. pulse/pulse pause 100/300 or 100/500 μs/μs). Used gases were nitrogen (10 or 80% of total flow) and hydrogen.

The hardness depth profiles of the plasma nitrided samples and forging dies were measured with a commercial hardness tester (Fischerscope, Vickers hardness $HV_{0.005}$) on polished cross sections. The microstructure was investigated with chemically etched cross sections. The etching fluid was Nital.

After nitriding, the forging tools were slightly sandblasted with aluminum oxide (average grit size 80–100 μm, pressure 2–3 bar) to remove the compound layer that can occur in dependency on the nitriding treatment.

The nitrided forging tools were tested under industrial conditions in serial forging tests to investigate the performance of the different treatments. This has been conducted at the Institute of Forming Technology and Machines (IFUM) in Hanover, Germany. A 300 t eccentric press (Co. Eumuco) was equipped with different nitrided testing tools (Fig. 2). The cycle times were 8 s in an automated process with billet handling, cooling and lubrication. The raw parts were made from DIN-42CrMoV4 (1.7225) with a composition of C=0.42%, Cr=1.10%, and Mo=0.25%. The geometry was prepared with a diameter of 30 mm and a height of 40 mm and the parts were heated in an inductive furnace to temperatures of 1150 °C.

After 1500 and 750 working strokes, when the main wear processes occurred the tools were investigated by optical microscopy. Cross-sections were prepared to analyze the crack depth and changes in the hardness depth profile.

3. Results and discussion

The nitriding parameters have a significant influence on the nitriding depth, the maximum hardness near the surface and the decreasing hardness gradient for a specific steel. Fig. 3 shows the results by means of nitriding hardness profiles for different treatments carried out for DIN-1.2343.

As diffusion is time dependent, the nitriding hardness depth (nhd) correlates with the nitriding time. Higher nitriding temperatures slightly increase the nitriding depth. This is determined by the temperature dependent nitrogen diffusion. Also plasma activation seems to play an important role. Comparing the hardness deviation of an intensive nitriding atmosphere ($N_2=80\%$) the higher activated plasma ($D=0.25$) creates a slightly increased nhd with a steeper gradient of the hardness profile. Additionally a distinct compound layer forms. To achieve high hardness penetration depths with a smooth hardness decrease and a reduced surface hardness, high nitrogen flows ($N_2=80\%$) and elevated nitriding temperatures are required. This is according to intensive nitriding conditions at 560 °C. Remarkable is the lower maximum hardness near the surface at higher nitriding temperatures (560 °C) in combination with a low nitrogen flow ($N_2=10\%$). Within this set of parameters a balance between the nitrogen flow at the surface and the thermal induced nitrogen diffusion in the steel substrate might be existent. In dependency on the nitrogen flow the formation of a compound layer could be observed: none with 10% N_2, approx. 10 μm with 80% N_2. The influence of the temperature on the formation of the compound layer was negligible.

The influence of plasma activation on the microstructure is described in Fig. 4 regarding the adjustment of the nitriding zone, the formation of compound layers and carbide precipitation. Lower temperatures in combination with less intensive plasma conditions are leading to microstructures with a minor precipitation of carbides on grain boundaries (Fig. 4a and c) and reduced or suppressed compound layers respectively. On the other hand the nitriding depth is higher with decreasing plasma activation (Fig. 4b and d).

Different samples of DIN-1.2343 with varying nitriding parameters according to Fig. 3 were investigated in the Rockwell indentation test. Cracks were observed in all cases but the crack shapes seem to be dependant of the nitriding

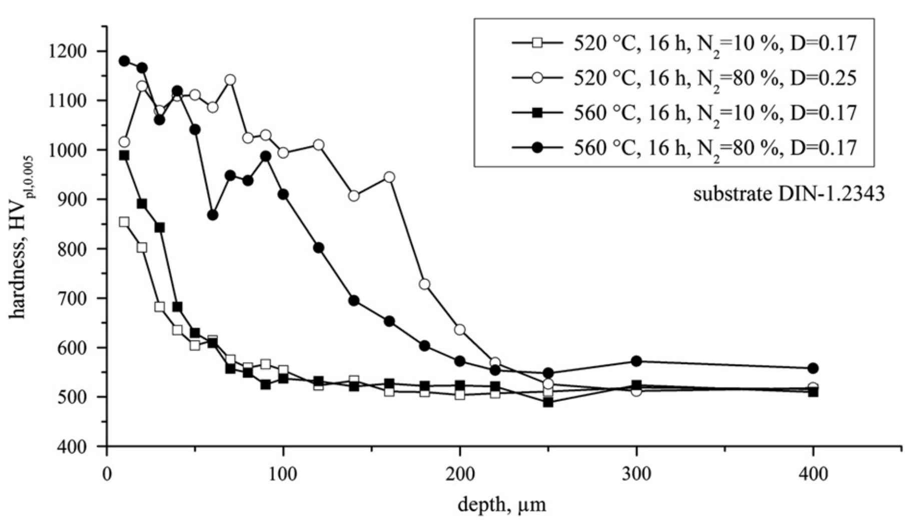

Fig. 3 – Hardness penetration profile of DIN-X38CrMoV5-1 hot forming steel in dependency on the nitriding parameters: duration, temperature and nitrogen mixture.

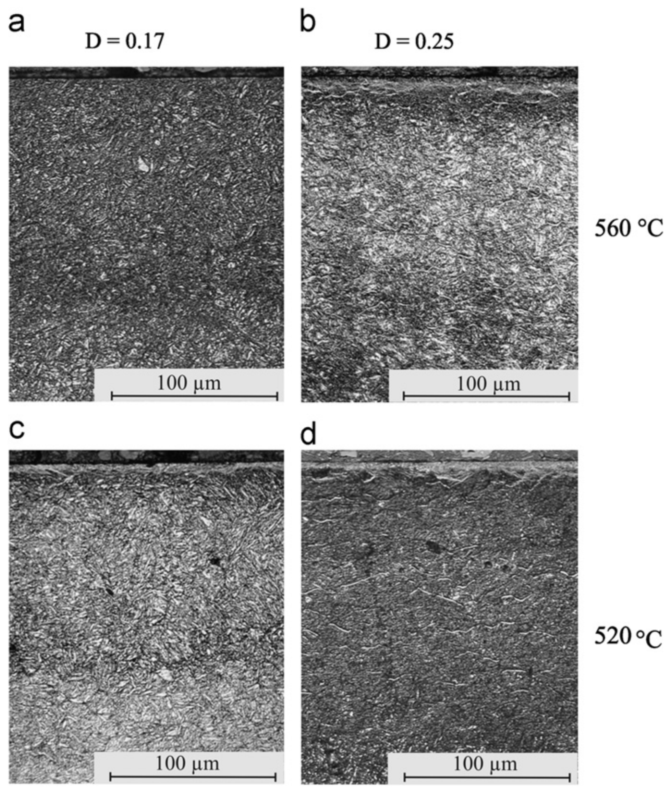

Fig. 4 – Pulse pause (PP) variation (plasma activation) influences the microstructure of nitrided DIN-X38CrMoV5-1 in processes of 16 h, N_2 80%.

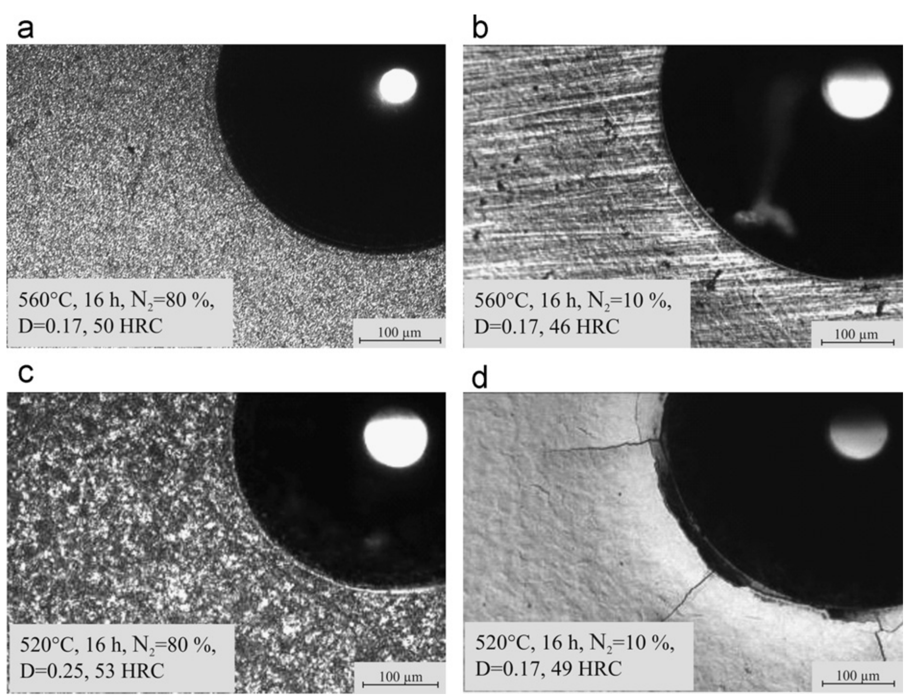

Fig. 5 – Crack behavior evaluated by Rockwell indentation test showing applied on nitrided DIN-X38CrMoV5-1 samples with different nitriding intensities.

process parameter sets. Typical patterns at lower nitriding intensities, which means low nitrogen contents with lower plasma activation (10% N_2, $D=0.17$), are mainly radial cracks (Fig. 5d) at low temperatures. Under same conditions but elevated temperatures (560 °C) the loading leads to patterns without any distinct cracks (Fig. 5b). With higher nitriding depth and compound layer structures on the surface caused from more intensive nitriding conditions the cracks are following the indent concentrically (Fig. 5a and c). At the same time, there is a correlation between the amount of deformation of the material caused by the Rockwell indentation and the nitriding depth which will be expressed in different indentation diameters. Smaller penetrations through higher nitriding depths are causing less material dislocation and therefore the crack intensity is lower. But for similar indentation diameters and corresponding nitriding depths there is found distinctive different crack behavior.

When high wear resistance is required and crack formation is not an issue, an intensified nitriding with an increased crack sensitivity may become the limiting factor in tool life. In this case the increasing nitrogen flow and/or nitriding time, which boosts the surface hardness and/or the nitriding depth, probably can reduce the crack resistivity under thermo shock conditions.

After performing application tests, i.e. forging of 1500 parts, all forging dies show obvious differences in their surface structures as shown in Fig. 6.

The focused wear critical zone within the tool geometry is flash path radius (marked in Fig. 6b), where high loads occur as a result of material flow in the closed engraving. The other wear critical region is localized at the center cone (inner part of the die). Here, coincidentally occurring wear mechanisms as thermal overloading and corresponding plastic deformation made it difficult to discuss the influence of nitriding on the crack behavior.

As reference, only hardened tools nearly shows no cracks but heavily worn out surface structures mainly caused from abrasive wear. In means of avoiding fatal cracking it seems to be a good idea not to modify the nearby surface zone. On the other hand the abrasive wear resistance due to the soft material properties is not sufficient.

Nitriding with low intensity (Fig. 6c) is promoting the formation of few but deep cracks which lead to severe cracking of bigger parts in the surface zone with continued forging process.

A qualitatively better surface by means of cracking and abrasive activity is achieved with an intensive nitriding (Fig. 6d) with high nitrogen contents in treatment atmosphere and more intensive plasma activation.

Fig. 7 shows composed cross sections of the wear relevant area after 750 and in case of the untreated reference 500 working strokes. They are showing different characteristics of crack quantity, crack depth and crack width in the investigation depending on the plasma diffusion treatment. The reference tool shows best performance according to crack sensitivity. Taking the resistance against wear and plastic deformation into account it shows the worst results analogous to Fig. 6a.

Tools treated at 560 °C for 16 h at 10% nitrogen in atmosphere and low nitriding intensity (Fig. 6b) are showing less crack sensitivity by means of the crack depth but even wider cracks. Compared to tools treated under same temperature conditions with intensive nitriding conditions (Fig. 6c) there is a remarkably higher quantity in small cracks.

Since an important failure criterion for surfaces seems to be the tendency to form interconnections between the cracks parallel to the surface, which will promote the flaking of small parts of material, the cracking depth is an important factor limiting the tool life.

Options for an optimization of tools with coincidental demands for low crack formation properties and abrasive wear resistance have been investigated with additional wear resistant coatings. (Please refer to 2nd contribution of the author team on AutoMetForm 2012 "The Potential of Plasma Deposition Techniques in the Application Field of Forging Processes" [14]).

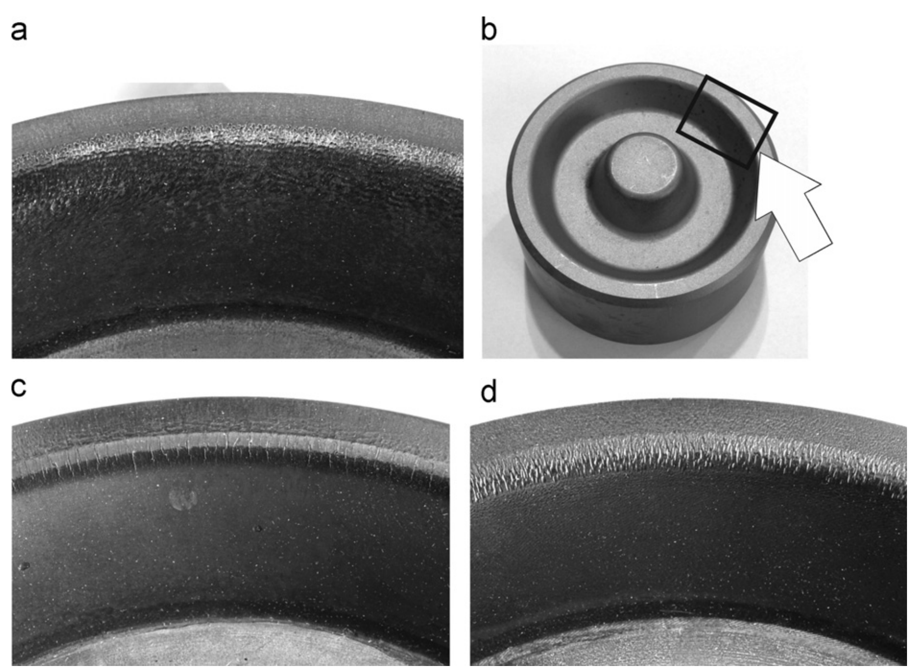

Fig. 6 – Surface of differently nitrided forging dies after 1500 forming operations in dependency on the nitriding parameters. The arrow is marking the relevant region of the tool. (a) Untreated, (b) wear critical zone, (c) 520 °C, 16 h, N_2=10%, D=0.17 and (d) 520 °C, 16 h, N_2=80%, D=0.25.

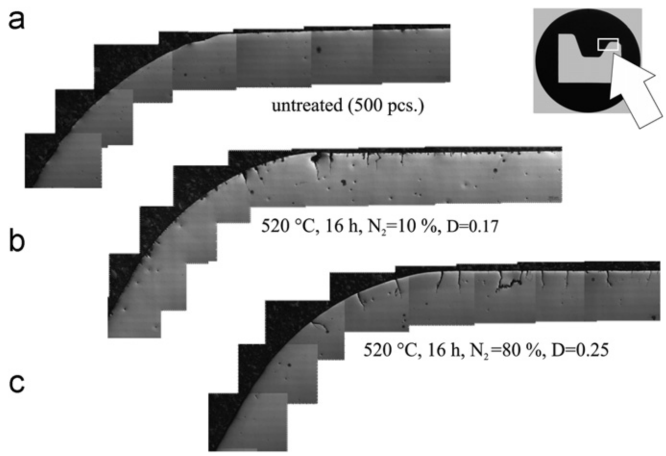

Fig. 7 – Crack pattern showed in cross sections of tools after 750 forming operations (untreated reference tool 500 operations) showing the influence of different treatments.

4. Conclusion

Under high mechanical loads as well as thermal shock conditions, which are the main characteristics of the forging process, adapted plasma nitriding under different conditions can clearly increase the crack formation in the hot forming tool steel DIN-X38CrMoV5-1 (1.2343). Especially the nitriding intensity, controlled through the parameters duty cycle and nitrogen content during the plasma process, is a decisive factor.

It could be shown that Rockwell indentations are suitable to evaluate the crack behavior of different nitriding treatments. Application tests with nitrided forging tools under industrial near conditions confirmed the influence on the wear behavior.

Applied to forging conditions, especially thermo shock conditions paired with high mechanical loads and abrasive/adhesive wear, nitriding of the tools at moderate temperatures (520 °C) in combination with a low nitrogen supply ($N_2=10\%$) at moderate plasma intensities ($D=0.17$) can reduce the crack formation significantly. The nitriding hardness depth is reduced but increasing abrasive wear may become an issue. Thus, additional wear resistant coatings probably can solve the problem.

For best results an individual optimization of the nitriding process is necessary.

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REFERENCES

[1] G. Castro, A. Fernandez-Vicente, J. Cid, Influence of the nitriding time in the wear behaviour of an AISI H13 steel during a crankshaft forging process, Wear 263 (2007) 1375–1385.

[2] M.U. Devi, T.K. Chakraborty, O.N. Mohanty, Wear behaviour of plasma nitrided tool steels, Surface and Coatings Technology 116-119 (1999) 212–221.

[3] R. Douglas, D. Kuhlmann, Guidelines for precision hot forging with applications, Journal of Materials Processing Technology 98 (2) (2000) 182–188.

[4] Y. He, I. Apachitei, J. Zhou, T. Walstock, J. Duszczyk, Effect of prior plasma nitriding applied to a hot-work tool steel on the scratch-resistant properties of PACVD TiBN and TiCN coatings, Surface and Coatings Technology 201 (2006) 2534–2539.

[5] J.-D. Kamminga, P.F.A. Alkemade, G.C.A.M. Jassen, Scratch test analysis of coated and uncoated nitrided steel, Surface and Coatings Technology 177-178 (2004) 284–288.

[6] T. Lampe, S. Eisenberg, E. Rodriguez Cabeo, Plasma surface engineering in the automotive industry—trends and future prospectives, Surface and Coatings Technology 174-175 (2003) 1–7.

[7] B. Navinsek, P. Panjan, F. Gorenjak, Improvement of hot forging manufacturing with PVD and DUPLEX coatings, Surface and Coatings Technology 137 (2001) 255–264.

[8] P. Panjan, I. Urankar, B. Navinsek, M. Tercelj, R. Turk, M. Cekada, V. Leskovsek, Improvement of hot forging tools with duplex treatment, Surface and Coatings Technology 151–152 (2002) 505–509.

[9] H. Paschke, M. Weber, P. Kaestner, G. Braeuer, Influence of different plasma nitriding treatments on the wear and crack behavior of forging tools evaluated by Rockwell indentation and scratch tests, Surface and Coatings Technology 205 (5) (2010) 1465–1469.

[10] K.-T. Rie, Recent advances in plasma diffusion processes, Surface and Coatings Technology 112 (1999) 56–62.

[11] J. Smolik, M. Gulde, J. Walkowicz, J. Suchanek, Influence of the structure of the composite: ‘nitrided layery/PVD coating’ on the durability of forging dies made of steel DIN-1.2367, Surface and Coatings Technology 180–181 (2004) 506–511.

[12] M. Stoiber, J. Wagner, C. Mitterer, K. Gammer, H. Hutter, C. Lugmair, R. Kullmer, Plasma-assisted pre-treatment for PACVD TiN coatings on tool steel, Surface and Coatings Technology 174–175 (2003) 687–693.

[13] M. Weber, P. Kaestner, H. Thomsen, H. Paschke, G. Braeuer, Influence of different plasma nitriding treatments on the wear behaviour of coated forging, in: Proceedings of Eleventh International Conference on Plasma Surface Engineering (PSE), Garmisch-Partenkirchen, 2008.

[14] T. Yilkiran, B.-A. Behrens, H. Paschke, M. Weber, H. Brand, The potential of plasma deposition techniques in the application field of forging processes, Archives of Civil and Mechanical Engineering, ⟨http://dx.doi.org/10.1016/j.acme.2012.06.002⟩, in press.