Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 37
ISSUE 2
December
2009

# Influence of chemical heat treatment on the mechanical properties of paper knife-edge die

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Received 21.09.2009; published in revised form 01.12.2009

**Properties**

## ABSTRACT

**Purpose:** In this article mechanical properties together with wear mechanism of paper knife-edge die made of A 681 steel with TiN, TiCN and DLC coating were analyzed. A Paper knife-edge die using in stamping machine, serves a map of complicated graphical projects. However wear resistance is strongly dependent on chemical composition of a paper mainly on the $TiO_2$ content.

**Design/methodology/approach:** In order to optimize the wear resistance of analyzed paper knife-edge die, influence of HS6-5-2 and A 681 substrate with Duplex treatment (vacuum nitriding/ TiN, TiCN and DLC antiwear coatings deposition) were compared. Morphology and mechanical properties (hardness, adhesion) were measured.

**Findings:** The present results show that the duplex treatment (nitriding/TiN) is a very promising technology for protection of paper knife-edge dies due to the uniform, dense structure with a high adhesion to the HS6-5-2 substrate. Hybrid layer fabricated by the gas nitriding and vacuum arc deposition presented improved mechanical properties.

**Research limitations/implications:** In further examinations to compare the results obtained for each layer it should be taken into consideration to manufacture the gradient DLC layers onto nitrided high-speed cutting steel. For full analysis of worked out technology additional examinations concerning investigation of friction coefficient and wear resistance and corrosion features of deposited layers should be conducted.

**Originality/value:** Our experiments provide in this case the evidence of increased mechanical properties of HS6-5-2 steel together with Duplex treatment (TiN coating) instead of A 681 substrate with TiN or TiCN coating.

**Keywords:** Wear resistance; Adhesion; Protective coatings (TiCN, TiN, DLC)

**Reference to this paper should be given in the following way:**
K. Dybowski, Ł. Kaczmarek, R. Pietrasik, J. Smolik, Ł. Kołodziejczyk, D. Batory, M. Gzik, M. Stegliński, Influence of chemical heat treatment on the mechanical properties of paper knife-edge die, Journal of Achievements in Materials and Manufacturing Engineering 37/2 (2009) 422-427.

## 1. Introduction

Designing of durability of a knife-edge die require the consideration of many important factors mainly: kind of cutting paper and kind of a power press. However, the most important thing is a material which knife-edge die is made. Most often materials used for cutting paper tools, are sintered carbides, cutting steel. Nevertheless, most general become cutting paper tools produced using powder metallurgy technology. Ceramics, regular boron nitride, synthetic materials are used too, however the most common materials for knife-edge die are high-speed steel and sintered carbides [1]. Cutting edges are subjected to a wear and following mechanisms are distinguished: chemical, adhesion, diffusion, thermal [2]. The most important criteria to analyze the wear of a cutting edge are following: geometry changes of cutting edge or lost in material, deterioration of a surface reflected in increase of roughness, enhance of a cutting or machining force [2, 3]. Improvement of mechanical properties of machine's parts and elements by hard coatings (due to grain size refinement, increases of defect density or present of residual compressive stress [4]) deposition is well known. However due to specific tribological properties of wood or paper, elements with a hard coatings in many cases do not guarantee sufficient protection against wear. At present, to increase wear resistance of cutting tools surface the following hard coatings are deposited: $Cr_xN$ [5], $TiN_x/Cr_{1-x}N$ [6], DLC [7], CrN [8], TiN [9, 10] TiC [11], superhard nanostructured TiAlBN [12], NbN – based multi-component [13]. They are synthesized using various techniques based on chemical and physical vapour deposition (CVD and PVD) methods or duplex treatment which is a combination of surface hardening e.g., heat treatment, ion implantation, thermo-chemical treatments [14, 15]. Due to that it is possible to cut paper with a higher speed even without cooling or lubricating medium.

However, relatively high hardness differences between substrate and coating together with poor adhesion might cause delamination effect and wear accelerate. It is an effect of plastic deformation of substrate under relatively high cyclic forces and thermal shock. In the light of presented results of research groups it seems that to overcome the tribological problems it is necessary to apply Functional Gradient Coatings (FGC) which should guarantee the continuous chemical and physical transition between substrate and outer layer [16-18].

The aim of this research was to increase coatings adhesion to the knife-edge die by material-treatment optimization. Three different coatings TiN, TiCN oraz DLC together with Duplex one were compared. Additionally, all results were compared with original knife-edge die made of A681 steel with TiN or TICN coatings.

## 2. Experimental details

### 2.1. Material and samples preparation

Commercial HS6-5-2 High Speed Steel was selected as sample material. Table 1 shows their chemical composition. The substrates were quenched and tempered to a mean hardness of $HV_{0,1}$. The substrate were polished mechanically to a surface finish of $R_a$=0.05 μm.

Table 1.
Chemical composition of high speed steel

| Substrate | Contents (wt%) | | | | |
|---|---|---|---|---|---|
| HS6-5-2 | C | Mn | Si | Ni | Mo |
| | 0.87 | 0.4 | 0.4 | 0.4 | 4.9 |
| | W | V | Co | Cr | Cu |
| | 6.6 | 1.7 | 0.5 | 4.2 | 0.3 |

### 2.2. Treatment and coatings deposition

Identifications of surface treatments and coatings are summarized in Table 2.

For gradient a-C:H/Ti layers synthesis (designated as process 3 and 4 – Table 2) hybrid plasmo-chemical RF PACVD reactor equipped with the pulsed magnetron sputtering system was used. Application of this kind of configuration make it possible to manufacture thick and well adherent diamond-like carbon layer onto surface of variety of metal substrates. Widely discussed in the world literature problem of internal stress and poor adhesion in the consequence was solved by the application of thin 100 nm thick Ti interlayer and deposition of gradient of the chemical composition from pure Ti on the substrate surface to thick DLC layer on the top. Due to application of Ti magnetron cathode it was possibile to improve the adhesion strenght of diamond-like carbon layer to the covered substrate. Moreover it is possible that titanium carbides which can occur in the amorphous carbon matrix ensure smooth connection of both phases appearing in the layers structure during the deposition process. More precise description of applied method was presented in our earlier works [19, 20]. Layers synthesized with use of presented technology are distinguished by the low friction coefficient, high hardness and wear resistance, moreover by good biological and corrosion parameters[21, 22,23]. Because of presented variety of parameters and very good correlation between it is possible that this kind of layers can be also applied in paper cutting industry. DLC were deposited according to following parameters: P = 1 - 20 [Pa], magnetron power 0,6 [kW], substrate's temperature < 200°C, self bias voltage 300 – 600 [V] gas atmosphere Ar and $CH_4$.

Table 2.
Identifications of surface treatments and coatings

| Process No. | Treatment/coating | substrate |
|---|---|---|
| 1 | TiN – original knife-edge die | A 681 |
| 2 | TiCN – original knife-edge die | |
| 3 | DLC 1 | HS6-5-2 |
| 4 | DLC 2 | |
| 5 | TiN | |
| 6 | TiCN | |
| 7 | Duplex TiN according to NITROVAC technology | |
| 8 | Duplex TiCN according to NITROVAC technology | |

Table 3.
Main process parameters for the TiN and TiCN coating depositon by Arc-PVD method

| | Atmosphere | Pressure $x10^{-2}$[mbar] | Temperature [°C] | U [V] | $I_{emission}$ [A] | Time [sek.] | Flow [sccm] |
|---|---|---|---|---|---|---|---|
| TiN | 100% $N_2$ | 1.2 | 400 | -150 | 80 | 1200 | 30 $N_2$ |
| Ti(C,N) | 25%C2H5+75%N2 | 2.0 | 400 | -200 | 80 | 1200 | 50 $C_2H_2$ |

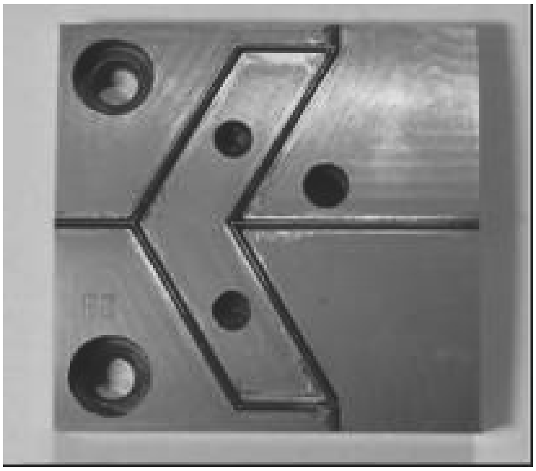

Fig. 1. View of a original paper knife-edge die

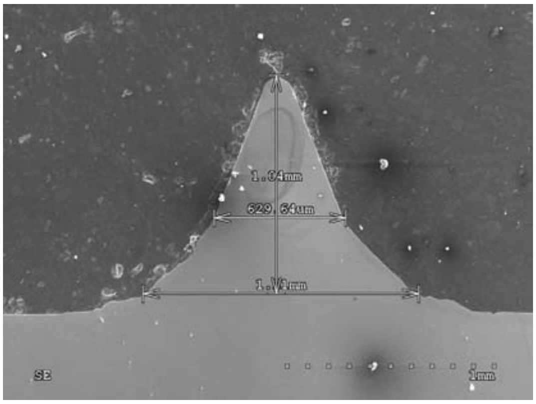


Fig. 2. Dimensions of a original paper knife-edge die

TiN and TiCN were deposited using Arc-PVD (designated as process 5-8 – Table 2) according to parameters shown in Table 3: Before coating doposition substrates were subjected to Ar plasma etching – P = 5 [Pa], U = 1.2 [kV], t = 20 [min.] and heating – P = 5 [Pa], U = 1.24 [kV], t = 60 [sek.].

Gas nitriding (designated as process 7 and 8 – Table 2) were realized according to NITROVAC technology [24], substrate's temperature 560°C, time 10,8 [ksek.], P = 25 [hPa].

Main process parameters for the TiN and TiCN coating depositon by Arc-PVD method are summarized in Table 3.

Morphology, microstructure and chemical composition of the coatings were investigated by means of scanning electron microscopy (SEM) and EDS with use of SEM S-3000 Hitachi. Nanoindentation testing was performed using a Nano Indenter G200 (Agilent Technologies) system, which is a modular system for nanoindentation, nanoscratch and nanoimpact testing.

For nanoindentation with a diamond Berkovich tip, the continuous stiffness measurement (CSM) mode was used, and the tip shape was calibrated by conducting experiments on a fused silica standard [25]. The data were analyzed using the Oliver and Pharr (1992) approach and nine repeated loading-partial unloading experiments were performed on each sample. The tests have been carried out at a strain rate of 0.05 $s^{-1}$.

# 3. Results and discussion

## 3.1. Analysis of an original paper knife-edge die

The view of the original knife-edge die at dimensions 55 x 53 x 10 mm made of steel A681 with hardness 730 $HV_{0.1}$, with TiN coating (thickness about 1.5 μm) is presented on Fig. 1. Additionally Fig. 2. shows the dimensions of the knife-edge die. The wear trace of the tool across crumbling up was showed on Fig. 3.

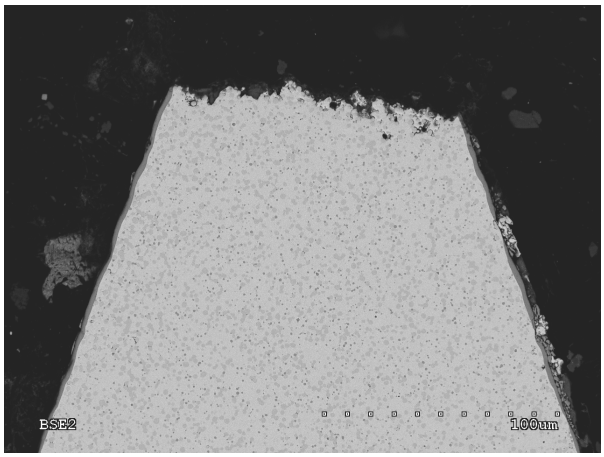


Fig. 3. SEM image of the wear trace of a paper knife-edge die

SEM microscopy analysis of the cutting edge on a few chosen tools proved the presence of lost in material in the antiwear layer. It was unambiguously affirmed during the investigation of the original tool that lost in materials is due to abrasive action phenomena in the antiwear layer and crumbling up the blade. To prevent knife-edge die following solutions were proposed: the change of the material from A681 on HS6-5-2, suitable thermal treatment and coating deposition: TiN or TiCN or DLC or duplex treatment (nitriding / TiN or nitriding / TiCN).

## 3.2. Coatings' properties

The hardness of original tools is lower the than value hardness of the titanium nitride and the titanium carbonitride deposited on substrate - steel HS6-5-2 (the Fig. 4). Additionally, TiN also has the lower adhesion to substrate - 35 N Fig. 5. DLC shows relatively high hardness 2225 and 2700 $HV_{0.1}$ process 3 and 4, respectively (nanohardness 25 and 30 GPa). However, their adhesion carries out 15 and 20 N, respectively. Layers on original cutting edge are thin and have about 1.5 µm in thickness (similarly as the thickness of DLC coatings - process 3 and 4) in the comparison with coatings from processes 5-8: TiN about 8.5 µm (Fig. 6), and TiCN about 3 µm (Fig. 7), Duplex - the nitrided layer about 4.9 µm, TiN coating about 8.5 µm (Fig. 8) and TiCN about 3.0 µm. The best solution is the change of the material to (HS6-5-2), nitrided layer, and then TiN antiwear coating deposition. Due to that continuous chemical and physical transition between substrate and outer TiN layer were received. This phenomena has direct shift on the adhesion increase of thin FeN – TiN sublayer. Cutting edge, covered to the principles of this solution, shows high hardness (above 2790 HV). Adhesion strength of TiN layer was above 45 N.

The TiCN layer presents high hardness level, moreover depended on the substrate material and pretreatment process. It is worth to notice that application of different substrate material resulted in noticeably increased hardness which proves that it is also very important to match correctly the substrate material. Much harder HS6-5-2 steel didn't yield to the plastic deformation as high as the one observed for A 681 substrate. Thus it can be stated that application of HS6-5-2 steel seems to be a good solution in order to improve the mechanical properties of the knife-edge die.

Adhesion of TiCN layer is also very high and there are no noticeable differences between each measurement performed for different substrates and pretreatments. The delamination of the coating occurred in the final range of the adhesion measurement process where the loads were in the range of 40 – 45 N. Although the adhesion level of TiCN coating was lower in case of duplex treatment than the one obtained for pure HS6-5-2 steel, it is worth to notice that application of additional hardening (nitriding) process should additionally prevent plastic deformations discussed earlier.

Adhesion of DLC layers was relatively lower than the one measured for the other types of layers. However it should be emphasized that because of high hardness of the layer it is also quite brittle. Moreover DLC layers were deposited only on pure HS6-5-2 steel surface without any additional surface hardening Therefore poor adhesion observed for this type of layers can be a reason of plastic deformation of the substrate which resulted in earlier layer delamination. Authors discussed this problem in earlier work [18], however last examinations of a-C:H/Ti layers deposited onto nitrided austenitic steel (hardness 1200 HV) gave very good results mostly in improvement of mechanical properties of gradient carbon layers (not presented in this paper). Thus it can be stated that maby hardness of high speed cutting steel is not high enough and additional nitriding process before the gradient carbon layer deposition should be conducted.

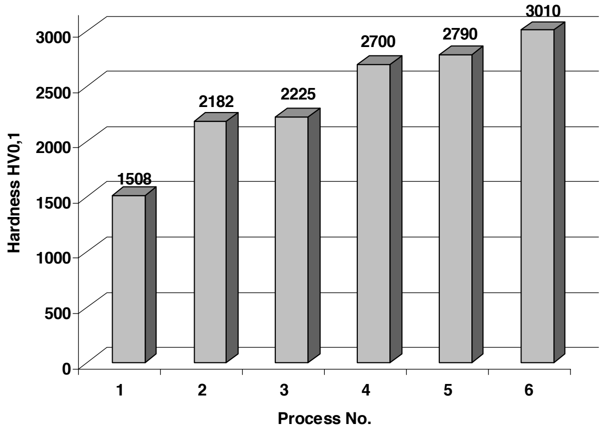


Fig. 4. Hardness of different coatings designed according to Table 2

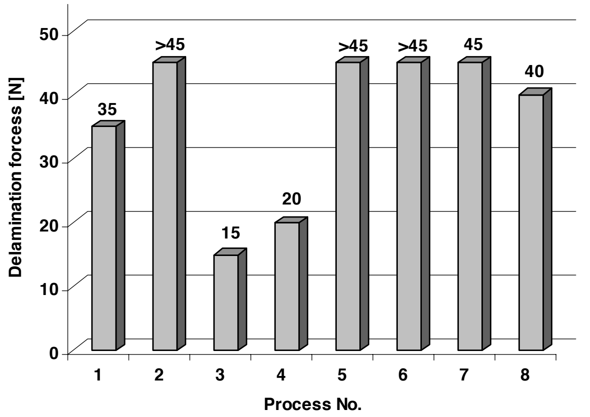


Fig. 5. Adhession of different coatings designed according to Table 2

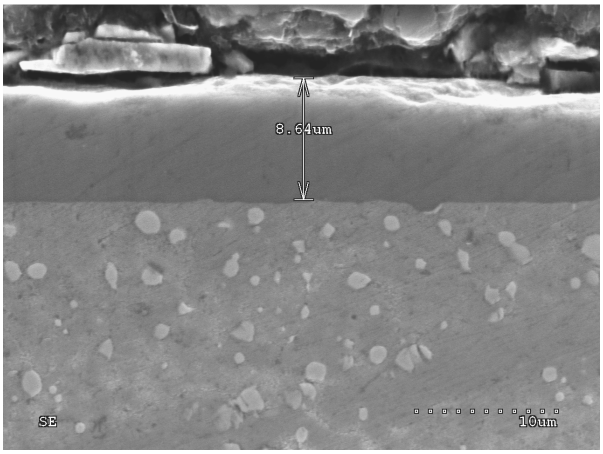


Fig. 6. SEM image of the TiN coating on to HS6-5-2 substrate – process no. 5

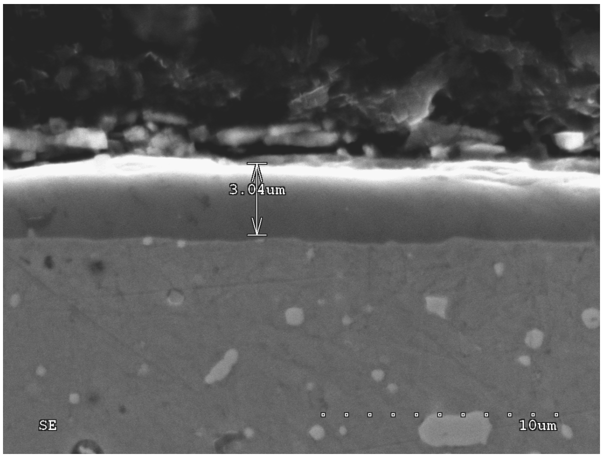


Fig. 7. SEM image of the TiCN coating on to HS6-5-2 substrate – process no. 6

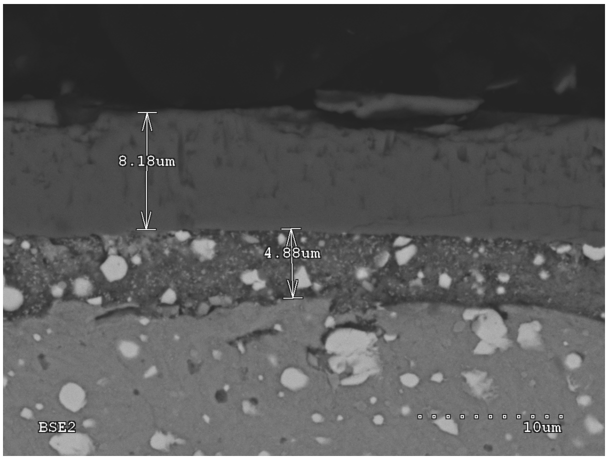


Fig. 8. SEM image of the Duplex TiN coating on to HS6-5-2 substrate – process no. 7

The change of the material should additionally lower the cost of the production of knife-edge die considerably. High speed steel HS6-5-2 is characterized by high hardness. Has less dispersed carbides in the structure than the original material, but it has very good mechanical proprieties despite of this. This steel is widely applied on tools due to good resistance on abrasion and high mechanical parameters.

Applying the best from proposed solutions to improve the durability of the of the tool the attention also should be put on the economic factor. First of all taking into consideration the price of the material applied in this solution (duplex treatment) as well as in the original knife-edge dies, their treatment and deposition of protective coatings, it can be estimated that this solution will reduce the cost the realization of the set of tools by about five times.

## 4. Conclusions

1. The present results show that the duplex treatment (nitriding/TiN) is a very promising technology for protection of paper knife-edge dies due to the uniform, dense structure with a high adhesion to the HS6-5-2 substrate.
2. Hybrid layer fabricated by the gas nitriding and vacuum arc deposition presented improved mechanical properties.
3. During the optimization of presented solutions concerning the material and technology it should be taken into consideration the economic factor, not to raise the costs of the production.
4. Proposed optimal solution is the TiN layer deposited on the nitrided H6-5-2 steel substrate – it will allow to increase the durability, hardness and wear resistance of the tool. It will also extend the time of work of such tool giving the possibility of the lowering of the costs of exchange.
5. In further examinations it should be taken into consideration deposition of gradient carbon layers onto nitrided high-speed cutting steel.
6. For full analysis of worked out technology additional examinations concerning investigation of friction coefficient and wear resistance and corrosion features of deposited layers should be conducted.

## Acknowledgements

Researches being a basis of this publication were financed from financial resources of the West Pomeranian Province budget.

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