Increasing in the wear resistance of injection molds made of 1.2343 steel using Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C nanocomposite coating

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Abstract. Injection molds used in production of plastic components are subject of heavy abrasion wear. The increase of their wear resistance significantly reduces the production cost. In the current work are presented research results of the wear resistance of injection molds made of steel 1.2343, coated with Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C. The study of the wear rate was done using the volumetric method and the influence of the trace length was investigated. The coating thickness, nanohardness, elastic modulus and adhesion were also tested. The coating was applied on unhardened ground specimens, hardened ground specimens and hardened polished specimens.

1. Introduction
The wear resistance of the tools in machine industry is a basic factor influencing on the productivity and production cost. Also, the wear of the tools results in a loss of accuracy of manufactured goods.

The injection molds work under very heavy conditions: heavy loads; high temperatures; significant wear. The tool's lifespan is directly linked to the wear of the working surfaces. Before tool's elaboration it is important to be known in advance the main factors influencing on the wear and working performance: the annealing depth (for annealed steels), the hardness of the tool's surface and the abrasive characteristics of the molded material (polymer) [1, 2, 3].

In order to increase the resource (life) of the injection molds, which going to lead to significant economic effect, it is necessary to take measures for increasing the hardness of the working surfaces of the tool and improving the wear resistance thereof. About the enhancement of these two properties, the methods for deposition of hard wear-resistant coatings are the most effective. Recently, the coatings obtained by the process of Physical Vapor Deposition (PVD) possess the most widely application [4, 5, 6, 7, 8, 9].
2. Aim of the work
This work aims to study the tribological characteristics of one PVD coating: Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C applied on samples of 1.2343 steel (usual material for molds making). To achieve this goal it was necessary to solve the following tasks:
- One manufacturing of test samples of 1.2343 steel and covering them with multilayer nanocomposite coating Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C by PVD method;
- A choice of methods for experimental investigation of tribological characteristics of the test samples with the above mentioned coating;
- A conducting of experimental studies;
- One analysis of results and conclusions.

3. Test samples preparation
To carry out the experimental studies, test samples of W. Nr. 1.2343 (DIN X38CrMoV5-1) steel which is used for the manufacture of injection molds were made in the form of a rectangular parallelepiped with dimensions shown in figure 1.

The samples were prepared as unhardened ground (denoted as 2343 A), hardened ground (denoted as 2343 B) and hardened polished (denoted as 2343 C). After their preparation they were covered with a PVD nanocomposite coating Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C. This coating was deposited by Closed Field Unbalanced Magnetron Sputtering (CFUBMS) industrial unit HVP100RHD in Nanotech Group Ltd., Plovdiv. Coating details could be found in [10]. Data about the test samples are listed in table 1.

![Figure 1. Shape and dimensions of the test samples.](image)

| Sample | Coating type | Hardness before deposition | Roughness of bare surface (Ra) | Roughness of coated surface (Ra) |
|--------|--------------|----------------------------|-------------------------------|-------------------------------|
| I1_2343A | unhardened ground | carbon-based | 145 HB | 0.191 µm | 0.199 µm |
| I1_2343B | hardened ground | nanocomposite | 52 HRC | 0.172 µm | 0.180 µm |
| I1_2343C | hardened polished | Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C | 52 HRC | 0.039 µm | 0.040 µm |
| E23_2343A | unhardened ground | without coating | 145 HB | 0.191 µm | - |
| E23_2343B | hardened ground | uncoated | 52 HRC | 0.172 µm | - |
| E23_2343C | hardened polished | uncoated | 52 HRC | 0.039 µm | - |

4. Methods for experimental investigation of tribological characteristics of the test samples

4.1. Method for experimental investigation of wear resistance of thin hard coatings
The experimental studies were conducted by "Ball on Flat Sliding Wear Test" friction scheme in a horizontal orientation of the test surface [11, 12]. One cemented-oxide ball (Al₂O₃) with diameter of 3 mm, fixed in holder, was used as a counter-part. It rubs a linear reciprocating sample without lubricant, working in air at room temperature [13, 14]. The width of the arise grooves was measured
by a microscope: PC based contactless measurement system TESA VISIO-300 at 100x magnification (resolution: 0.001 mm).

The average width value \( b_{cp} \) was calculated:

\[
b_{cp} = \frac{1}{n} \sum_{i} b_i, \text{ mm}
\]  \hspace{1cm} (1)

where:
- \( n \) – number of the grooves (traces);
- \( b_i \) – width of every particular groove.

The wear rate \( I_w \) was worked out by the equation:

\[
I_w = \frac{V}{F L}, \text{ mm}^3/\text{N.m}
\]  \hspace{1cm} (2)

where:
- \( V \) – the wear volume (volume of the trace), \( \text{mm}^3 \);
- \( F \) – the normal load upon the ball, \( \text{N} \);
- \( L \) - the sliding distance between the ball and sample, \( \text{m} \).

The volume of the track was determined by the methodology described in [11].

4.2. Methods for investigation of thickness, nanohardness, elastic modulus and adhesion of the coating

The thickness of the coating is a key complex indicator and was measured by one calotester elaborated in CLAP-Plovdiv. It was implemented a ball with a diameter of 30 mm and the coating thickness \( h \) was calculated by the well-known formula [15, 16]:

\[
h = \frac{D^2 - d^2}{8R} \cdot 10^{-3} \left[ \mu \text{m} \right]
\]  \hspace{1cm} (3)

where:
- \( D \) - the outer section diameter, \( \text{mm} \);
- \( d \) - the inner section diameter, \( \text{mm} \);
- \( R \) - the ball radius, \( \text{mm} \) (here: 15 mm).

Nanohardness and elastic modulus of the coating were examined using Compact Platform CPX (MHT/NHT) CSM Instruments in CLAP-Plovdiv. A diamond indenter (Berkovich type) was used and the results were interpreted by the Oliver and Pharr method [17,18].

The adhesion was tested by Micro Scratch Tester (MST) module included in the same apparatus. A diamond indenter (Rockwell type) with rounded apex of 200 \( \mu \text{m} \) was used [19].

5. Experimental researches and results

5.1. Investigation of influence of the sliding distance on the wear rate

Table 2 contains summary data about the volume of wear traces over test samples as a function of sliding distance \( V=f(L) \) in the respective regimes.

| Sliding distance \( L, \text{ m} \) | 11_2343A \( 10^{-6}, \text{ mm}^3 \) | 11_2343B \( 10^{-6}, \text{ mm}^3 \) | 11_2343C \( 10^{-6}, \text{ mm}^3 \) | E23_2343A \( 10^{-6}, \text{ mm}^3 \) | E23_2343B \( 10^{-6}, \text{ mm}^3 \) | E23_2343C \( 10^{-6}, \text{ mm}^3 \) |
|---|---|---|---|---|---|---|
| 50 | 901.729 | 418.526 | 29.532 | 7247.592 | 4713.143 | 4528.021 |
| 75 | 940.461 | 868.726 | 72.978 | 9673.319 | 8790.414 | 8232.896 |
| 100 | 1583.903 | 1000.620 | 77.524 | 9885.18 | 9580.145 | 9603.382 |
Diagrams of the volume of wear traces of coated and reference (uncoated) samples in the respective regimes are shown in figures 2÷5.

**Figure 2.** Graphical dependence of the volumes of wear traces of coated samples as a function of sliding distance \( V=f(L) \).

**Figure 3.** Graphical dependence of the volumes of wear traces of coated and reference (uncoated) samples made of unhardened ground 1.2343 steel as a function of sliding distance \( V=f(L) \).

**Figure 4.** Graphical dependence of the volumes of wear traces of coated and reference (uncoated) samples made of hardened ground 1.2343 steel as a function of sliding distance \( V=f(L) \).

**Figure 5.** Graphical dependence of the volumes of wear traces of coated and reference (uncoated) samples made of hardened polished 1.2343 steel as a function of sliding distance \( V=f(L) \).

Table 3 contains summary data about the wear rate as a function of sliding distance \( I_w=f(L) \) in the respective regimes.
Table 3. Wear rate as a function of sliding distance $I_w=f(L)$. 

| Sliding distance $L$, m | $11\_2343A$ | $11\_2343B$ | $11\_2343C$ | $E23\_2343A$ | $E23\_2343B$ | $E23\_2343C$ |
|-------------------------|-------------|-------------|-------------|--------------|--------------|--------------|
|                         | $10^{-6}$, mm$^3$/N m | $10^{-6}$, mm$^3$/N m | $10^{-6}$, mm$^3$/N m | $10^{-6}$, mm$^3$/N m | $10^{-6}$, mm$^3$/N m | $10^{-6}$, mm$^3$/N m |
| 50                      | 18.035      | 8.370       | 0.591       | 144.952      | 94.263       | 90.560       |
| 75                      | 12.539      | 11.583      | 0.973       | 128.978      | 117.206      | 109.772      |
| 100                     | 15.839      | 10.006      | 0.775       | 98.852       | 95.801       | 96.034       |

Diagrams of the wear rate as a function of sliding distance $I_w=f(L)$ are shown in figures 6-9.

**Figure 6.** Graphical dependence of the wear rate of coated samples as a function of the sliding distance.

**Figure 7.** Graphical dependence of the wear rate of coated and reference (uncoated) samples made of unhardened ground 1.2343 steel as a function of sliding distance $I_w=f(L)$.

**Figure 8.** Graphical dependence of the wear rate of coated and reference (uncoated) samples made of hardened ground 1.2343 steel as a function of sliding distance $I_w=f(L)$.
Experimental results indicate that the sliding distance influences on the wear of the carbon-based nanocomposite Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C coating, thereby increasing the sliding distance causes a wear increase also. The wear rate of this coating applied on a hardened polished surface is average 12.8 times less than that on a hardened ground surface and average 19.8 times less than that on an unhardened ground surface.

5.2. Investigation of thickness, nanohardness, elastic modulus and adhesion of the coating

On the base of the calotester measurement, the calculated thickness is 2.32 μm. A nanoindentation curve of the test sample 11_2343C is shown in figure 10. These parameters were specified: nanohardness $H = 18$ GPa; elastic modulus $E = 320$ GPa; maximal penetration depth $h_m = 309$ nm (at maximal indentation load of 30 mN). The maximal penetration depth is less than 15% of the entire coating thickness (2.32 μm), which guarantees that the measured nanohardness is related mostly to coating without a substrate impact.

![Figure 9](image9.png)  
**Figure 9.** Graphical dependence of the wear rate of coated and reference (uncoated) samples made of hardened polished 1.2343 steel as a function of sliding distance $I_w=f(L)$.  

![Figure 10](image10.png)  
**Figure 10.** Nanoindentation load/unload curve of sample 11_2343C: Load $F$ versus indenter displacement $h$.  

$I_w.10^{-6}$, mm$^3$/N m
Figure 11. Scratch test of sample 11_2343C: a) curves of the applied force $F_n$ and friction coefficient $\mu$ as a function of scratch distance $s$; b) view of the trace.

Figure 11a shows the results obtained by the adhesion test (scratch distance of 3 mm). The force $F_n$ which presses the indenter was changed linearly to a maximum value of 30 N (the maximum load allowed by this equipment). The first obvious damages in the coating were originated by applied force of ca. 19 N (figure 11b and curve of $\mu$ in figure 11a). These damages are internal (cohesive) and their appearance marks the first critical load: $F_{c1}$. Since a delamination of the coating (an exposure of the substrate) in the channel is not noticed, it is proven that the second critical force $F_{c2}$ is not reached up to maximal applied force (30 N).

6. Conclusions
- The discussed carbon-based nanocomposite Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C coating does not change the primary surface roughness. This is mainly due to a lack of droplets during the coating deposition when using the methods of Magnetron Sputtering (MS). The appearance of droplets is a major shortcoming of other PVD methods: Vacuum (Cathodic) Arc Deposition (VAD, CAD), Pulsed Laser Deposition (PLD), etc. which increases the roughness;
- The quality of the surfaces on which a carbon-based nanocomposite Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C coating is deposited, has a significant impact on the wear of the coating. When surface roughness decreases and/or hardness increases, the wear rate of the coating is reduced;
- The calculated wear rate of the considered carbon-based nanocomposite Ti/TiN/TiCN/nc-TiCN:a-C/nc-TiC:a-C/a-C coating deposited on a hardened polished surface is average $7 \div 11$ times less than that on a hardened ground surface and average $16 \div 20$ times less than that on an unhardened ground surface;
- The measured hardness and adhesion show a coating with a relative lower hardness (on the edge of conventional limit for hard coatings: 20 GPa) and a passable adhesion. This low hardness shows the apparent presence of graphite phase in the coating, which phase, however, favors a low coefficient of friction. The relatively weak adhesion is probably due to the significant stress in the coating. It is mainly due to the differences in the nature and parameters of the bonds Ti-N and Ti-C and such stress is often observed in coatings based on TiCN.

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