Tribological properties of DLC coating under lubricated and dry friction condition

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Abstract. Increasing demands on reducing abundant use of environmentally hazardous lubricants like chlorinated paraffin oil in production motivates extensive research on dry friction condition. However, the dry friction condition is not favourable, and it causes high friction and severe wear problems. This paper presents the tribological behaviour of a new hard coating, namely double-layer DLC/TiAlN, deposited onto the tool steel surface via a Physical Vapour Deposition (PVD) process. A pin-on-disk tribometer was used to study the long-term performance of DLC/TiAlN coated tool steel under lubricated and dry friction conditions. Surface damage after the experiment was observed by using a light optical microscope (LOM) and also, analysed by measuring wear scar profiles with a tactile roughness profilometer. The results were compared with uncoated tool steel. Based on the experimental result, applying the DLC/TiAlN coating to the tool steel surface has led to a significant reduction of friction and almost no wear scar was observed. The study proved that the DLC/TiAlN coating contributes to the better wear life of the tool steel, thereby improving the tool lifetime.

1. Introduction
In all mechanical systems, friction and wear happen when moving components in contact with each other. Poor lubrication has always been the reason to high friction, and leads to severe wear and surface damage. Often the industries do not have a specific procedure on how to treat lubricants, and they never check the lubricants or ask for certifications [1]. This is due to the lack of fundamental understanding on the issues which could be attributed to the lack of research and development activities among them. Highly skilled workers are the only one that can solve these issues. Large amount of efficient but hazardous lubricants like chlorinated paraffin oils are seen as the effective solution which produce an instant result. This is favourable by the industries that see the instant profit and high productivity as their priority.

Instead of utilizing lubricants, applying hard coating on tool substrate is one of the common methods to reduce friction and to prevent wear. A great number of hard coatings are available for protecting the tool steel surface, such as TiN, CrN, TiAlN [2], AlCrN [3], TiC and TiCN [4,5]. At present, Diamond-like Carbon (DLC) coating has gained acceptance in various industries, for example, automotive, medical, and tooling components, owing to its several attractive properties, including the low friction coefficient, high hardness, good wear resistance, and protection of the tool steel surface. These properties make DLC coatings suitable for many tribological applications in mechanical systems, such as valve train tappets, gears, and piston pins [6,7]. Unfortunately, depositing single DLC coating
layer onto the tool steel surface alone is insufficient, since the single-layer DLC coating can easily be delaminated and thereby impractical to protect the tool steel surface from severe wear and surface damage. A comparison between multi-layer coatings and a single layer deposited onto the substrate tool [8,9] has shown that the multilayer coating was able to add degree of freedom in tailoring the coating properties [10,11]. This is related to the combination of toughness and adhesion strength of the interlayer coating [12], which plays an important role in tribological system. In the present study, the long-term tribological performance of a new hard coating, namely DLC/TiAlN, deposited on tool steel Vanadis 4 by PVD process, were evaluated and compared with uncoated tool steel. The present paper investigates the tribological behaviors of both uncoated and coated tool steel under lubricated and dry friction condition as one of the possible efforts in improving the tribological conditions that exist in almost all mechanical components of the two sliding surfaces.

2. Materials and method

2.1. Materials

The tool steel material is a powder metallurgical cold work tool steel (Vanadis 4) with high C and Cr contents that was alloyed with Mn, Mo, Si, and V. The tool steels were through-hardened, tempered to 62 HRC, and subsequently polished to a surface roughness $Ra$ of 0.02 µm before the coating was applied. The ball indenter material fitted to the pin holder was a commercially available steel, 100 Cr6, with a ball diameter of 6 mm. Table 1 presents the mechanical properties and the compositions of the test materials used in the experiments.

| Components       | Composition                          | Mechanical Properties |
|------------------|--------------------------------------|-----------------------|
|                  |                                      | Density $\rho$ (g/cm$^3$) | Poisson ratio $\nu$ | Elastic modulus $E$ (GPa) |
| Tool steel       | 1.4% C, 0.4% Si, 0.4% Mn, 4.7% Cr, 3.5% Mo, 3.7% V | 7.56 | 0.3 | 200 |
| (Vanadis 4)      |                                      |                       |                   |
| Indenter ball    | 1.0% C, 0.25% Si, 0.35% Mn, 1.5% Cr  | 7.81 | 0.3 | 210 |
| (Steel 100 Cr6)  |                                      |                       |                   |

2.2. Coating

A double-layer a-C:H type DLC/TiAlN coating was studied, and its performance was compared with the uncoated tool steel as shown in Figure 1(a). The double-layer DLC/TiAlN coating film shown in Figure 1(b) was deposited onto the tool steel substrates (Vanadis 4, with a surface hardness of 62 HRC) via a Physical Vapour Deposition (PVD) process based on unbalanced magnetron sputtering. The tool steel roughness after coating was the same as before: $Ra = 0.02$ µm. The top-layer a-C:H type DLC coating was chosen because it has mixture of carbon bonds of sp$^3$, sp$^2$, and even sp$^1$, with the possible presence of hydrogen, in the DLC that promotes a good combination of high wear resistance and low friction for preventing wear [13,14]. Meanwhile, the inter-layer TiAlN was chosen owing to the high content of Al in the TiAlN coating, which results in high hardness, reducing the wear and extending the tool steel lifetime for improved productivity [15]. Figure 1(c) shows the a-C:H type DLC supported by two other coating films—CrN and CrCN—which acted as bonding layers that were deposited onto the TiAlN-coated die surface. Coating binders, CrN, and Cr interlayer coatings were added to the DLC coating in the form of a gradient coating structure. The mechanical properties and surface characteristics of the test coating are presented in Table 2, where the uncertainty values represent the observed variations in the investigated areas.
2.3. Tribological test

A pin-on-disk tribological test shown in Figure 2 was performed to analyze the long-term performance of the DLC coated and uncoated tool steel surfaces that reproduce the motions and forces that occur in mechanical systems engineering applications, i.e. bearings, internal combustion engines, metal cutting, and metal forming. The test parameters applied in the tribological experiment can be seen in Figure 2 (right). Figure 3 presents a tactile roughness profilometer and a light optical microscope (LOM) used to investigate wear scar on the DLC coated and uncoated tool steel surfaces after the experiments.

![Figure 1: Test specimen made of tool steel Vanadis 4 – a) uncoated, b) double-layer DLC/TiAlN, and c) DLC/TiAlN coating structures.](image1)

![Figure 2: Schematics of the laboratory pin-on-disk tribological test (left) and test parameters applied in the experiment (right).](image2)

| Coating     | Thickness (µm) | Hardness (HV) | Roughness Ra (µm) |
|-------------|----------------|---------------|-------------------|
| DLC/TiAlN  | 4 ± 0.40       | 3,000         | 0.026             |

![Figure 3: Diagram showing the long-term tribological performance of the DLC coated and uncoated tool steel surfaces after the experiments.](image3)

3. Results and discussion

The experiments were carried out in both lubricated and dry friction condition for a friction pair consisting of a 100Cr6 steel ball and a Vanadis 4 tool steel flat surface with and without a double-layer a-C:H DLC/TiAlN coating with a contact load of 10 N, at ambient temperature of 32° C and a relative moisture of 68% +/- 2%, with the constant sliding rate and the total sliding distance being 100 mm/s and 8000 mm, respectively.

The diagram in Figure 3(a) shows the long-term tribological performance of the DLC coated and uncoated tool steel exposed to lubricated and dry friction condition. The lowest value of the friction coefficient in steady-state condition was observed for the specimens with a-C:H type DLC/TiAlN coatings in both lubricated and dry friction condition. The highest value of the friction coefficient was reported for the Vanadis 4 tool steel specimens without coatings tested under both lubricated and dry friction condition. Regardless of lubrication condition, it should be noted that the friction coefficient was much lower for the...
tool steel specimen with the DLC/TiAlN coating than for the specimen without coating. This could be attributed to the excellent wear-resistant properties of the DLC coating, in which supported by an improved adhesion strength from the TiAlN interlayer coating [16]. These combined characteristics are essential for improving the tool steel lifetime.

The influence of coating is significant. Larger friction coefficient can easily be observed in Figure 3(a) when no coating is applied to the tool steel during operation. Running the long-term experiment has revealed that the DLC/TiAlN coating is capable to reduce the frictional effects and reached a stable value after long-hour experiment. In order to measure this noticeable improvement for the DLC/TiAlN coated tool, roughness measurement on the wear scar profiles were employed with an optical profilometer for each sample. The wear scar images were captured using LOM. Figure 3(b) presents the wear scar images of the DLC coated and uncoated tool under dry friction condition by analyzing the depth and width of both worn surfaces after the pin-on-disk experiment. Based on these results, it is possible to see only minor scratches that is found on the wear track of the DLC/TiAlN coated tool. This can be related to the excellent toughness and good wear resistance of the DLC/TiAlN coating than can function with and without the presence of oil film. These characteristics are essential proof, in which the coating can contribute to the better wear life of the tool steel, thereby improving the tool lifetime.

![Figure 3](image_url)

**Figure 3:** a) Friction coefficient and b) wear scar profiles of the uncoated and coated tool steels.

### 4. Conclusion

The tribological properties of the DLC/TiAlN coated and uncoated tool steels were evaluated successfully in both lubricated and dry friction condition. The present study adopted a pin-on-disk tribometer for emulating tribological conditions that exist in almost all mechanical components of the two sliding surfaces. The experimental results indicate that in the presence of no lubricant at all, the values of the friction coefficient were significantly lower for the specimen made of Vanadis 4 tool steel coated with a-C:H DLC/TiAlN than for the uncoated specimen. As shown by the LOM images and surface profiles of the worn surfaces, the DLC/TiAlN coating contributes to almost no surface damage either in lubricated condition or in dry friction condition, and this is directly related to a significant reduction in the friction coefficient. The use of DLC as the top layer coating and TiAlN as an interlayer coating in the present study revealed that their combined excellent tribological properties, including low-friction, anti-wear, high toughness and good adhesion strength, provide an environmentally-friendly alternative to outperform conventional approaches utilizing hazardous lubricants in production, which are toxic.

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