Research Article

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Performance evaluation of titanium-based metal nitride coatings and die lifetime prediction in a cold extrusion process

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Abstract: Surface coating can greatly enhance the lifetime of cold extrusion die. It is a significant issue to evaluate the performance of coatings and even predict the lifetime of cold extrusion die. In this work, the titanium-based nitride coatings including TiN, TiAlN, and TiAlCrN were, respectively, deposited on the surface of high-speed steel substrate $W_6Mo_5Cr_4V_2$ (M2) by the physical vapor deposition technology. The hardness test, scratch test, Rockwell adhesion test, and pin-on-disc (POD) wear test were carried out aiming to investigate the performances of the three coatings including hardness, adhesion strength, and wear resistance. The results show that the TiAlCrN coating exhibits the highest hardness of 3,033 HV in comparison with TiN coating (1,222 HV) and TiAlN coating (1,916 HV), while it possesses poor adhesion strength and inferior wear resistance. Furthermore, the TiAlN coating presents the highest resistance to wear and spalling from the substrate. In addition, the Archard wear model of the coatings was solved and applied in the finite element model of cold extrusion to calculate the wear depth and lifetime of the cold extrusion dies. The results suggest that TiAlN coating is the optimal option for cold extrusion die as compared with TiAlCrN and TiN coatings. TiAlN coating can prolong the lifetime of the substrate die up to 260%.

Keywords: titanium-based nitride coating, performance, finite element method, Archard model, cold extrusion

1 Introduction

The excellent performance, especially lifetime, of tools and dies is pursued in a high efficient production, and how to extend their lifetime is an urgent and significant issue. Surface coating, as a booming technique, has been increasingly applied to extend the lifetime of dies [1]. Physical vapor deposition (PVD) is a key surface coating method, which produces the thin film coatings with different nanocomposite structures and properties that can be configured to meet the performance requirements of many different applications [2]. PVD coatings result in extreme surface hardness, low coefficient of friction (COF), anti-corrosion, and wear resistance properties. According to different requirements, PVD proposes multiple options of nanocomposite coatings that have unique properties based on the materials used in the coating. Among which, titanium nitride (TiN) is the most common PVD hard coating in use in improving tool and die lifetime today, as it has an ideal combination of hardness, toughness, adhesion, and inertness [3]. In these years, the concept of second-generation Ti(X)N coatings has been proposed on the basis of first-generation TiN [4]. Ti(X)N coatings where X stands for metallic element introducing to the TiN lattice have been subjected to great interest. The most important of second-generation Ti(X)N includes ternary titanium TiAlN and quaternary titanium TiAlCrN, which shows more excellent wear resistance and oxidation resistance than TiN.

Reverse extrusion cold forming is the main forming process for the forgings with deep holes. It has advantages in three aspects including high productivity, low cost, and increased physical properties [5]. The punches and dies used in cold extrusion are subjected to severe working conditions such as high pressure, high shear

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forces, and sometimes rapid frictional heating [6]. Consequently, the punches and dies are high deformation possible and high wear possible without tearing the metal. Usually they are made of wear-resistant tool steel, e.g., high chromium steels, but the performance and life are facing great challenges. Although the PVD coating of first-generation TiN has been a good solution, the more excellent performance and longer life are always pursued, and then second-generation Ti(X)N is always in development. Munz [7] prepared ternary titanium TiAlN coating to substitute the TiN coating, and his measuring results showed that both the hardness and cohesive strength were improved significantly. Rabinovich et al. [8] designed quaternary titanium TiAlCrN coating, and his comparison results with TiAlN coating showed that the TiAlCrN coating can be served as a reliable protective layer for cutters. Kara et al. investigated the influence of processing parameters on the wear resistance of TiN, concluding that the wear rate is higher in the vacuum condition compared to atmospheric condition [9]. In his work, the wear coefficient for the TiN coating is in the range of 2.78×10^{-8} to $3.73 \times 10^{-7} \text{ mm}^3/\text{N} \times \text{mm}$. Drozd et al. studied the property improvement of AlCrSiN coating to K340 tool steel and found that AlCrSiN coating can reduce the COF and wear rate of K340 tool steel [10]. The COF of AlCrSiN coating is reported as 0.529 and wear factor as $5.68 \times 10^{-7} \text{ m}^3/\text{N} \times \text{m}$. Kumar et al. investigated the friction and tribological behavior of bare nitrided, TiAlN and AlCrN coated MDC-K hot work tool steel [11] and found that TiAlN coating exhibits lower wear rate and superior micro-hardness compared to bare nitride and AlCrN coated surface. In general, a common conclusion was achieved that the coatings improve the lifetime of tools and dies.

The multiple options of nanocomposite coatings should be optimized by a series of evaluation indicators. Hardness is a significant property of coatings in the application of cutting tools [12]. The coatings with higher hardness can dramatically improve the lifetime of dies and realize the processing of difficult-to-process materials [13]. In practice, the coating only works when it adheres to the substrate. The adhesion strength, as a considerable indicator, is usually characterized by the shedding degree between coating and substrate [14]. Furthermore, the wear resistance of coatings is another significant indicator considered as a comprehensive reflection of coating properties and always used to evaluate the lifetime of dies by Usui and Shirakashi [15] or Archard [16] wear model. In addition to the above, it is significant how to present the wear performance of the dies with designed PVD coatings used in cold extrusion. Finite element method (FEM) simulation of a cold extrusion

process provides a good solution [17]. The main variables including friction coefficient and surface hardness in a FEM model of die wear simulation come from experimental measurements. The simulations were then conducted, and then the wear distribution of cold extrusion die was uncovered.

In the present work, the TiN coating, TiAlN coating, and TiAlCrN coating were prepared by PVD technology. Hardness test, scratch test, Rockwell adhesion test, and POD pin disc wear test were carried out to evaluate the performance of the coatings including hardness, adhesion, and wear resistance. The Archard wear model for the cold extrusion die with PVD coatings was solved based on the results of above tests, and then a FEM model implanted by Archard wear model was established for the die wear issue in a cold extrusion process. The wear depth and wear distribution of cold extrusion die were computed based on the FEM simulations; meanwhile, the die lifetime was evaluated.

2 Preparation for titanium-based metal nitride coatings

PVD method was adopted to prepare the coatings in the present study. The material of coating substrate was high-speed steel $\text{W}_6\text{Mo}_5\text{Cr}_4\text{V}_2$, whose chemical compositions are presented in Table 1, and the block samples with the size of $20 \text{ mm} \times 19 \text{ mm} \times 5 \text{ mm}$ were machined from the forged billet. All samples were gas quenched to hardening the coating substrate and stabilizing the substrate size. To reduce the effects of matrix roughness on coating, the sample surfaces were grinded and mechanical polished. Subsequently, the samples were rinsed with clean water and placed in an ultrasonic cleaning instrument with absolute ethanol for further cleaning. Then, the clean samples were fetched out to dry. After that, the samples were, respectively, coated with TiN, TiAlN, and TiAlCrN in a vacuum arc-ion plating instrument. The inner pressure of the instrument is about $6 \times 10^{-3} \text{ Pa}$, and the voltage is controlled in the range of 50–100 V. The coated and uncoated samples were presented in Figure 1 which showed that the $\text{W}_6\text{Mo}_5\text{Cr}_4\text{V}_2$ substrate was in slivery, TiN coating in cash yellow, TiAlN coating in

Table 1: Chemical compositions of the $\text{W}_6\text{Mo}_5\text{Cr}_4\text{V}_2$ substrate (wt%)

Element	C	W	Si	Mn	Cr	Mo	V	Fe
Content	0.95	6	0.3	0.3	4	5	2	Balance

Figure 1: The prepared samples of (a) $W_6Mo_5Cr_4V_2$ substrate, (b) TiN, (c) TiAlN, and (d) TiAlCrN coating on $W_6Mo_5Cr_4V_2$ substrate.

dark purple, and TiAlCrN coating in pale purple. The thickness of the deposited coatings is seriously limited in the range of 5.9–6.1 μm . Finally, a series of tests were carried out including hardness test, adhesion strength test, and friction and wear test. The performance of different coatings was evaluated in the following sections.

3 Characterization of mechanical performance of coatings

3.1 Microhardness of coatings

The HV-1000 Vickers' microhardness tester was used to characterize the microhardness of coatings. For the sake of avoiding crushing the coatings, the payload adopted in experiment must be limited in a proper range. Its value can be estimated roughly according to equation (1) before the microhardness tests. The principles for the preliminary design of experimental payload are as follows: first, the thickness of the coating should be 1.5 times of the average length of indentation diagonal; second, for ferrous alloys, the center distance of two indentations and the distance from indentation center to sample's edge should be larger than 2.5 times of the average length of indentation diagonal. As for nonferrous alloy, it is five times [18]. The experiment payload F (N) is expressed as follows [19]:

$$F = 2.35 HVt^2, \quad (1)$$

where t represents the thickness of coating in millimeter, and HV represents the estimated Vickers hardness of material. In the present study, the thickness of coatings is about 0.006 mm; the Vickers hardness of the coatings is in the range from 1,200 to 3,500 HV. Consequently, the

experiment payload is estimated as 0.10152–0.2961 N. The final experiment payload was taken as 0.2425 N, corresponding with the Vickers hardness symbol HV0.025. Then, the microhardness tests were performed. Four points were, respectively, picked out from each sample to represent the microhardness values of samples. The average Vickers hardness of $W_6Mo_5Cr_4V_2$ substrates, TiN, TiAlN, and TiAlCrN coatings were measured as 792, 1,222, 1,916, and 3,033 HV, respectively. Correspondingly, the Rockwell hardness of the samples can be obtained as 63, 74, 83, and 89 HRC, respectively, based on equation (2).

$$\begin{aligned} \text{HRC} &= \frac{100 \times \text{HV} - 15,100}{\text{HV} + 223} & \text{HV} > 520, \\ \text{HRC} &= \frac{100 \times \text{HV} - 13,700}{\text{HV} + 223} & 200 \leq \text{HV} \leq 520. \end{aligned} \quad (2)$$

3.2 Adhesion of coatings

The adhesion between coating and substrate can be evaluated using Rockwell hardness experiment and scratch testing. The procedure of the Rockwell hardness experiment is as follows: by pressing an indenter into the surface of the material with a specific load and then observing the vicinity of the indentation. Usually, cracks and delamination may appear around the indentation. The density of cracks and the delamination extend are related to the shedding degree of coatings. Vidakis *et al.* divided the shedding degree into six levels, as shown in Figure 2 [14]. The slight shedding corresponding to a few cracks or a mild delamination is acceptable failure, while the extensive peeling of coatings is unacceptable. The optical metallography images of indentations for TiN, TiAlN, and TiAlCrN coating were obtained from the present Rockwell hardness experiments, as shown in Figure 3. The image corresponding to TiN coating is characterized by a few cracks around the indentation. It corresponds to the

Figure 2: Reference standard for adhesion strength in Rockwell hardness test [14].

shedding degree of level one. That means the adhesion of TiN coating is acceptable. The image of TiAlCrN coating shows a lot of microcracks around the indentation, which corresponds to the shedding degree of level two. It is still acceptable. As for the TiAlN coating, there are almost no cracks or delamination around the indentation, which means the TiAlN coating has superior adhesion compared with the TiN coating and TiAlCrN coating.

To further evaluate the adhesion of the coatings, scratch tests were performed. The scratch testing process involves a hard tip being drawn across the surface of a material with an applied gradually increasing load, forming a scratch. The vertical load, tangential friction force, and acoustic signal in the scratching process are caught and recorded over time. The experimental parameters for the scratch tests are listed in Table 2. The

Figure 3: Optical metallography images of indentations for (a) TiN coating, (b) TiAlN coating, (c) TiAlCrN coating. Note: The images in the first line are in 100 $\times$, while the images in the second line are in 500 $\times$.

Table 2: Experiment parameters for scratch test

Scratch type	Initial load (N)	Maximum load (N)	Loading rate (N/min)	Scratch length (mm)
Single scratch	5	120	30	3

scratch morphologies of TiN, TiAlN, and TiAlCrN coatings were characterized and shown in Figure 4. Correspondingly, the relationships of acoustic signal and friction force with applied load are exhibited in Figure 5. It is obvious that the width of the scratches is narrow at the initial stage of the tests. Meanwhile, the acoustic signal fluctuates in a small range, and the tangential friction force gradually increases in a small gradient. As the load increases and the stylus moves ahead, the scratches

become more and more pronounced. With the further increase in the load to a critical value, microcracks and furrows appear around the scratches.

The adhesion strength of coatings can be characterized by the critical load that is the minimal load for the collapse of coating. The critical load can be identified based on the acoustic signal and friction force features. The sudden change in acoustic signal or the sharp rise in friction force represents the occurrence of coating fracture. Accordingly, the applied load at such moment is regarded as critical load. Higher critical load means stronger adhesion strength. The critical load for TiN coating is identified as 61.5 N, TiAlN coating as 87 N, and TiAlCrN coating as 49 N. Therefore, it can be concluded that the TiAlN coating is capable of better adhesion performance than TiN coating and TiAlCrN coating,

Figure 4: Scratch morphologies of (a) TiN coating, (b) TiAlN coating, (c) TiAlCrN coating.

Figure 5: Acoustic wave and tangential friction varying with the applied load for various coatings: (a) TiN coating, (b) TiAlN coating, (c) TiAlCrN coating.

which is in good agreement with the results obtained from Rockwell hardness experiments.

3.3 Wear resistance of coatings

Generally, the wear resistance of material can be evaluated by Archard wear model or improved Archard wear model [16, 20]. In the classic theory of Archard model, the contact interface of the friction pairs is a plane, and the high micro-convex body at the interface would be more

readily subjected to the load and thus causing stress concentration. Once the stress exceeds the yield strength of friction material, the micro-convex body with lower yield strength will undergo plastic deformation and then peeling off. Wear coefficient, as an indicator independent of the loading parameters, is usually used to characterize the wear resistance of material. Its expression is as equation (3) [16].

$$k = \frac{\Delta V \times H}{L \times F} = \frac{\pi \times S \times H}{F}, \quad (3)$$

Table 3: Experimental parameters of HT-2001 POD pin disc wear tester

Load (N)	Rotate speed (mm/s)	Lubrication condition	Temperature (°C)	Humidity
5	72	Non-lubricated	25	40%

where k represents the wear coefficient, ΔV is the wear volume which can be measured by wear experiment, H is the surface hardness of material, F is the normal loading force, L represents the sliding distance, and S represents the cross area of wear traces which can be measured by surface profiler.

The wear experiments were carried out on a HT-2001 pin-on-disc sliding wear tester. The experimental procedure includes the following steps. First, a grinding ball equipped with a force sensor was pressed against the surface of samples. Meanwhile, a relative sliding was exerted

between the grinding ball and sample. Subsequently, the profile of the wear trace was extracted and then the wear coefficient was figured out. According to Kara *et al.* [9], the experiment condition will have significant influence on the wear rate. Consequently, the experiment parameters should be uniform, especially temperature and humidity. The preset experimental parameters are shown in Table 3. To make sure that the profile of the wear traces is more visible and easier to be measured, the wear time for substrate, TiN coating, TiAlN coating, and TiAlCrN coating is set as 400, 1,800, 1,800, and 2,400 s, respectively, and the corresponding radius of wear paths is set as 6, 6, 10, and 10 mm, respectively. A Dektak 150 surface profiler with resolution of 10^{-11} mm was applied to extract the profile of the wear tracks. The surface profiles of the wear traces corresponding to substrate and different coatings were derived and shown in Figure 6. It is apparent that the profile of the wear traces shows an approximate U-shape. In addition, it is noteworthy that there is a bulge at the

Figure 6: Surface profile of wear traces: (a) substrate, (b) TiN, (c) TiAlN, (d) TiAlCrN.

indentation of wear scratch for TiAlN coating. It may be caused by the hard microparticles precipitated from the TiAlN matrix [21]. Based on the sliding distance and the cross area of the profiles, as well as the loading load, the wear coefficients can be derived. The statistical results and calculated wear coefficient of the substrate and coatings are presented in Table 4. Apparently, the wear resistance of TiAlN coating is better than that of other coatings and substrate. The wear resistance of PVD coatings is lower than that of the substrate, which implies that the deposited titanium-based nitride coatings can reduce the wear of the $W_6Mo_5Cr_4V_2$ substrates. In addition, the wear coefficient of these titanium-based nitride coatings is obviously lower than that of AlCrSiN coating [10]. It can be attributed to the superior hardness of the titanium-based nitride coatings. The measured wear coefficient of TiN coating is consistent with the result that was reported by Kara et al. [9]. Comparing the wear coefficient of the PVD coatings with one and each other, it can be found that the TiN coating possesses similar wear resistance with the substrate $W_6Mo_5Cr_4V_2$ steel, while the wear coefficient of TiAlN and TiAlCrN coatings is obviously higher. The reason is that many hard particles exist in TiAlN and TiAlCrN, hardening the matrix and enhancing the wear resistance of materials. However, for the TiAlCrN coating, even though it has the highest hardness, the adhesion of TiAlCrN coating is the worst among the three coatings. On the whole, TiAlN coating has the highest wear resistance because of the simultaneous high hardness and strong adhesion.

Besides, the COF of the substrate and coatings is recorded and shown in Table 4. The COF in the present work is in the range of 0.18–0.37, which is obviously lower than that of Drozd et al. [10]. This is mainly because the PVD coatings in the present study possess higher hardness. Comparing the COF of the substrate and coatings, it is apparent that the PVD coatings can significantly lower the COF of the substrate, which would benefit to the forming process of cold extrusion.

4 Lifetime prediction of cold extrusion die based on FEM analysis

It is well known that the wear is the main form of die failure in a cold extrusion process [22]. Therefore, it is significant to study the wear behavior of cold extrusion die and further to predict the lifetime of die. In this work, the numerical analysis based on FEM is used to simulate the actual cold extrusion process. The failure of cold extrusion die is defined as not being able to get repaired and service continuously when the total wear depth reaches the intolerant amount of wear, and the total number of products produced by the same die is defined as the service life of cold extrusion die.

4.1 FEM simulation for cold extrusion process

The cold extrusion process is a complicated forming process involving deformation, heat transfer, and wear, which can be divided into two parts: upsetting and extrusion. Schematic diagram of cold extrusion process is shown in Figure 7(a). The simulation of cold extrusion process was performed on the solving platform, DEFORM. The FEM model was simplified as a plane model for improving the calculation efficiency and is shown in Figure 7(b). In the model, all the bodies were automatically meshed by four-node quadrilateral finite element formulation and their initial temperature was set as room temperature. Steel 45 was applied for the cylindrical billet with a diameter of 18 mm and a height of 17 mm, and $W_6Mo_5Cr_4V_2$ for the matrix of cold extrusion die with a fillet radius of 2 mm. The friction coefficient was assumed to be shear type and was set based on the measured result in experiment. The heat transfer coefficient between the

Table 4: Measurement result of related parameters and the calculated wear coefficient

Sample	Hardness (HV)	Sliding distance (mm)	Loading force (N)	Cross-sectional area (mm ²)	Wear coefficient	Coefficient of friction
Substrate	792	180,956	5	20.5674×10^{-6}	1.296×10^{-7}	0.37
TiN	1,222	814,300	5	56.4008×10^{-6}	1.214×10^{-7}	0.25
TiAlN	1,916	1,357,168	5	22.3286×10^{-6}	7.985×10^{-8}	0.18
TiAlCrN	3,033	1,809,557	5	30.2408×10^{-6}	9.786×10^{-8}	0.23

Figure 7: Schematic diagram of cold extrusion process and its FEM model.

deformed material and dies was defined as 0.033. The forming speed was 86 mm/s.

To analyze the wear behavior of cold extrusion die and further predict the lifetime of die that is coated with different coatings, the Archard wear model for the coatings needs to be solved and implanted into the cold extrusion FEM model. The Archard model for the cold extrusion process can be expressed as equation (4) [16].

$$W = \int K \frac{P^a \times v^b}{H^c} dt, \quad (4)$$

where W is the wear depth; a , b , and c are constants, here, $a = 1$, $b = 1$, $c = 2$; P is the interface pressure; and v is the relatively sliding speed. K and H are wear coefficient and hardness of material, respectively, which have been obtained from the above mechanical property tests.

It is well known that the wear behavior of die is strongly associated with the deformation process of billet. Therefore, it is essential to analyze the forming process of billet aiming to clarify the wear process of cold extrusion die. Here, the forming process of cold extrusion has been simulated. The stress fields corresponding to different extrusion moments are shown in Figure 8. A significant difference is noticed that the material mainly deformed in the punch corner area in Figure 8(a), while it concentrates in the bottom of top die in

Figure 8: Nephograms of stress field distribution of billet at different extrusion moments: (a) start point, (b) end point.

Figure 9: Nephograms of velocity field at different extrusion moments: (a) start point, (b) end point.

Figure 10: Nephograms of temperature field at different extrusion moments: (a) start point, (b) end point.

Figure 11: Nephograms of cold extrusion die corresponding to (a) interface pressure, (b) interface temperature, and (c) wear depth. Note: the curve represents the specific value along the bottom boundary of the die; the bottom center is the original point.

Figure 8(b). In addition, the distributions of temperature field and the velocity field are also shown in Figures 9 and 10, respectively. It is apparently found that the

material in the punch corner area shows high temperature and severe material flow. The results indicate the heavy wear of cold extrusion die will occur here.

Figure 12: Finite element simulation procedures of the die lifetime for cold extrusion process.

To intuitively uncover the wear behaviors of the three coatings, the cold extrusion process was simulated. Taking the cold extrusion die of TiN coating as an example to show the simulated results, the interface pressure, the interface temperature, and the wear distribution of cold extrusion die are shown in Figure 11. It is obvious that both the temperature distribution in Figure 11(a) and interface pressure distribution in Figure 11(b) show a similar tendency to that of the wear distribution in Figure 11(c), where the punch corner area shows the highest level. The simulated wear distribution of the top

die is in agreement with the results that deduced the forming process analysis. It is worth noting that there is relatively high interface pressure in the bottom center of top die, while the wear depth is still shallow. It suggests that the wear of cold extrusion die is determined by the comprehensive effect of temperature and interface pressure as well as the wear resistance of materials. For the sake of comparing the wear behaviors of the substrate and the coatings, the cold extrusion process was simulated using different parameter configuration that corresponds to the three coatings. The maximum wear depth of the top dies during once cold extrusion is recorded as 8.355×10^{-7} mm for $W_6Mo_5Cr_4V_2$ substrate, 4.424×10^{-7} mm for TiN coating, 1.622×10^{-8} mm for TiAlN coating, and 2.492×10^{-8} mm for TiAlCrN coating.

4.2 Lifetime prediction of cold extrusion die

During the actual cold extrusion process, if the wear depth of the top die reaches 0.006 mm, the die would be defined as wear failure. The simulation procedures of die lifetime can be classified as three steps: simulating the cold extrusion process once, then extracting the temperature history and stress history during the cold extrusion process, finally calculating the wear depth of dies for each cycle of cold extrusion process until the wear depth reaches 0.006 mm. Following the simulation procedures in Figure 12, the lifetime for every element on the cold extrusion die can be predicted.

Figure 13: The simulated lifetime of (a) $W_6Mo_5Cr_4V_2$ substrates die, (b) TiN coating die, (c) TiAlN coating die, and (d) TiAlCrN coating die.

The simulated die lifetime nephograms for the substrate and PVD coatings are shown in Figure 13. The minimum in the nephograms represents the lifetime of the die. Consequently, based on the finite element simulation, the die lifetime of $W_6Mo_5Cr_4V_2$ substrate, TiN coating, TiAlCrN coating, and TiAlN coating is predicted as 7,154, 13,564, 25,669, and 24,081, respectively. It is noted that all three coatings can improve the wear resistance of the substrate die and prolong the die lifetime, and the TiAlN coating possesses the strongest wear resistance. It can prolong the $W_6Mo_5Cr_4V_2$ substrate die lifetime up to 260%.

5 Conclusion

In this work, the performance of titanium-based nitride coatings including TiN, TiAlN, and TiAlCrN was evaluated based on a series of mechanical property tests. Furthermore, the wear behaviors of die in a cold extrusion process were uncovered, and the die lifetime was predicted by FEM simulation. The following conclusions have been drawn from the results of present investigation.

- (1) The TiAlCrN coating exhibits the highest hardness of 3,033 HV in comparison with TiN coating (1,222 HV) and TiAlN coating (1,916 HV).
- (2) The wear resistance of materials comes from the synthesis influence of adhesion and hardness. The wear resistance of $W_6Mo_5Cr_4V_2$ substrate and titanium-based nitride coatings is ranked in the following order: $W_6Mo_5Cr_4V_2 < TiN < TiAlCrN < TiAlN$.
- (3) The lifetime of cold extrusion die was predicted based on finite element simulation. All three coatings can improve the die lifetime of $W_6Mo_5Cr_4V_2$ substrate, and TiAlN coating shows the most significant effect on the die lifetime improvement. It can prolong the lifetime of the substrate die up to 260%.

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References

- [1] Sous, F. C. V. and J. G. Francisco. Recent advances on coated milling tool technology – a comprehensive review. *Coatings*, Vol. 10, No. 3, 2020, id. 235.
- [2] Mattox, D. M. Handbook of physical vapor deposition of physical vapor deposition (PVD) processing, 2nd edn. William Andrew Publishing, New York City, 2010, pp. 553–734. doi: 10.1016/B978-0-8155-2037-5.00021-6.
- [3] Zhang, S. Y. and W. G. Zhu. TiN coating of tool steels: a review. *Journal of Materials Processing Technology*, Vol. 39, No. 1–2, 1993, pp. 165–177.
- [4] Vancoille, E., J. P. Celis, and J. R. Roos. Mechanical properties of tin, (Ti,Al)N, (Ti,Nb)N and Ti(C,N) coatings measured by nano-indentation. *Tribology*, Vol. 25, 1993, id. 311.
- [5] Giardini, C., E. Ceretti, G. Maccarini, G. Pellegrini, and A. Bugini. Models and experimental results in plastic deformation processes: The reverse extrusion. *Journal of Materials Processing Technology*, Vol. 32, No. 1–2, 1992, pp. 335–343.
- [6] Dincu, P. P., A. Achimas, and N. E. Adriana. Numerical simulation of tool wearing in reverse cold extrusion processes. *Acta Technica Napocensis Series-Applied Mathematics Mechanics and Engineering*, Vol. 60, No. 2, 2017, pp. 263–268.
- [7] Munz, W. Titanium aluminum nitride films: A new alternative to TiN coatings. *Journal of Vacuum Science & Technology A*, Vol. 4, 1986, pp. 2717–2725.
- [8] Rabinovich, G. S., A. I. Kovalev, M. H. Aguirre, B. D. Beake, K. Yamamoto, S. C. Veldhuis, et al. Design and performance of AlTiN and TiAlCrN PVD coatings for machining of hard to cut materials. *Surface and Coatings Technology*, Vol. 204, No. 4, 2009, pp. 489–496.
- [9] Kara, L., D. Özkan, M. Barış Yağcı, E. Sulukan, Y. Sert, and T. Sonsuz Sert. Friction and wear behaviors of TiN coatings under dry and vacuum conditions. *Tribology Transactions*, Vol. 62, No. 3, 2019, pp. 362–373.
- [10] Drozd, K., M. Walczak, M. Szala, and K. Gancarczyk. Tribological behavior of AlCrSiN-coated tool steel K340 versus popular tool steel grades. *Materials*, Vol. 13, No. 21, 2020, pp. 4895–4910.

- [11] Kumar, S., S. R. Maity, and L. Patnaik. Friction and tribological behavior of bare nitrided, TiAlN and AlCrN coated MDC-K hot work tool steel. *Ceramics International*, Vol. 46, No. 11, 2020, pp. 17280–17294.
- [12] Ducros, C., V. Benevent, and F. Sanchette. Deposition, characterization and machining performance of multilayer PVD coatings on cemented carbide cutting tools. *Surface and Coatings Technology*, Vol. 163–164, 2003, pp. 681–688.
- [13] Kim, J. S., G. J. Kim, M. C. Kang, J. W. Kim, and K. H. Kim. Cutting performance of Ti–Al–Si–N-coated tool by a hybrid-coating system for high-hardened materials. *Surface and Coatings Technology*, Vol. 193, No. 1–3, 2005, pp. 249–254.
- [14] Vidakis, N., A. Antoniadis, and N. Bilalis. The VDI 3198 indentation test evaluation of a reliable qualitative control for layered compounds. *Journal of Materials Processing Technology*, Vol. 143–144, No. 1, 2003, pp. 481–485.
- [15] Usui, E. and T. Shirakashi. Analytical prediction of cutting tool wear. *Wear*, Vol. 100, 1984, pp. 129–151.
- [16] Archard, J. F. Contact and rubbing of flat surfaces. *Journal of Applied Physics*, Vol. 24, No. 8, 1953, pp. 981–988.
- [17] Giuliano, G. Process design of the cold extrusion of a billet using finite element method. *Materials & Design*, Vol. 28, No. 2, 2007, pp. 726–729.
- [18] Ollendorf, H. and D. Schneider. A comparative study of adhesion test methods for hard coatings. *Surface & Coatings Technology*, Vol. 113, No. 1–2, 1999, pp. 86–102.
- [19] Heinke, W. Evaluation of PVD nitride coatings, using impact, scratch and Rockwell-C adhesion tests. *Thin Solid Films*, Vol. 270, No. 1, 1995, pp. 431–438.
- [20] Liu, R. and D. Y. Li. Modification of Archard's equation by taking account of elastic/pseudoelastic properties of materials. *Wear*, Vol. 251, 2001, pp. 956–964.
- [21] Odén, M., L. Rogström, A. Knutsson, M. R. Ternér, P. Hedström, J. Almer, et al. In situ small-angle x-ray scattering study of nanostructure evolution during decomposition of arc evaporated TiAlN coatings. *Applied Physics Letters*, Vol. 94, 2009, id. 053114–1.
- [22] Kang, J. H. A study on a die wear model considering thermal softening: (I) Construction of the wear model. *Journal of Materials Processing Technology*, Vol. 96, No. 1–3, 1999, pp. 53–58.