A Method for Evaluating the Impact Wear Behavior of Multilayer TiN/Ti Coating

Xin Cao, Weisheng Xu and Weifeng He*

Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University, Xi’an 710038, China; studentcaoxin@163.com (X.C.); researcherjj@163.com (W.X.)
* Correspondence: hehe_coco@163.com

Received: 13 January 2020; Accepted: 28 January 2020; Published: 3 February 2020

Abstract: An energy-controlled cycling impact test was applied to evaluate the impact wear behavior of hard coating. A multilayer TiN/Ti coating with a total thickness of ~10 µm, containing two TiN layers and two Ti layers, with the thickness ratio of these two kinds of the layers being 9:1, was chosen as the research object. The impact velocities were 60, 120, and 180 mm/s, and the impact cycles were $10^2$, $10^3$, and $10^4$, respectively. Damage morphology observation and numerical simulation were used to analyze the failure mechanisms. The results show that the contact time keeps almost constant under different impact velocities and cycles. Impact peak forces remain unchanged with increasing cycles at the same velocity, but they increase linearly with impact velocities, reaching a maximum value of 262.26 N at 180 mm/s. The energy dissipated rate (EDR) increases from 31.58% at 60 mm/s to 35.59% at 180 mm/s, indicating the degenerative toughness. Two impact-wear failure mechanisms are found in impact zones of the coating; these are peeling and circular cracks. Peelings are induced by cycling high-stress gradients in hard layers and interfaces. Circular cracks are caused by cycling tensile stresses in the form of fatigue at the edge of impacted pits.

Keywords: energy-controlled impact; multilayer TiN/Ti coating; energy dissipated rate; impact damage failure

1. Introduction

Titanium alloys, owing to their excellent strength and corrosion resistance, are widely applied in the aerospace industry [1]. Their poor wear resistance, however, affects the service life of corresponding components, such as engine casings, compressor blades, and so on [2–4]. Coating techniques have been rapidly developed, and it is possible to apply coatings to these component substrates, which results in superior performance in a number of aspects [5]. Applying hard coatings to component surfaces is an effective method to improve the wear resistance of the substrates. They provide excellent wear protection due to their sufficient hardness, but they are prone to suffer from sustained impact and might be susceptible to fracture and spalling in the substrate when operating in harsh environments, due to their brittleness. Most recent research has focused on the wear resistance of hard coatings but does not explore the impact wear performance of hard coatings. Therefore, it is necessary to investigate the impact wear behavior of hard coatings.

The maximum impact force is often used as a test control condition adopted by most studies on impact wear behavior [6–11]. Knotek [6] developed a repetitive impact test in which a ceramic ball could be made to impact the surface of materials at different cycles and with different magnitudes of impact force. Matthews [7] used a repetitive impact test to evaluate the fatigue properties of thin TiN coatings working under dynamic load and found three types of damage failures on the wear zones of coatings, including circular cracks, cohesive peeling, and adhesive peeling. Lawes [8], Abdollah [9], Chen [10], and Bouzakis [11] conducted the repetitive impact test, and the devices they used were...
all based on a force-controlled mode. However, it is difficult to obtain the response and evolution of the material during the test process, which becomes a major shortcoming of the force-control mode testing machine.

To avoid the above disadvantage, a kinetic-controlled cycling impact device was designed in this paper. The most widely used coating in engineering, the multilayer TiN/Ti coating, was chosen to be experimented on with this device under different impact velocities and cycles. The impact wear behavior including dynamic mechanical response and failure mechanisms were investigated. The impact wear damage morphologies of wear zones were observed to analyze the failure mechanisms.

2. Materials and Methods

2.1. Coatings Preparation

Titanium alloy (Ti6Al4V) with dimensions of 20 mm × 20 mm × 3 mm were selected as substrates for the deposition of multilayer TiN/Ti coatings due to their wide applications in the aerospace industry. The substrates were mechanically ground and polished to a mirror surface (Ra 0.018 µm). All specimens were ultrasonically cleaned in acetone and in alcohol and then dried with nitrogen. A four-layer TiN/Ti coating, which had the best impact wear performance among the multilayer TiN/Ti coatings according to previous studies [12], was deposited by the Filtered Cathodic Vacuum Arc (FCVA) deposition technique. The multilayer coating contained two TiN layers and two Ti layers with the total thickness being 10 µm. The volume fraction of the Ti layer in the multilayer TiN/Ti coating was 10%. In order to achieve a high adhesion of coatings, a large dose of Ti ion was injected into the sublayer of substrates using metal vapor vacuum arc (MEVVA) technology before and after the Ti adhesive layer deposition. The specific injection and deposition parameters are shown in Table 1. The cross-sectional microstructure of the coating was observed with a scanning electron microscope (TESCAN MIRA 3, Brno, Czech Republic) and is shown in Figure 1. The actual total thickness of TiN/Ti coatings is about 10.81 µm, and the structure is in accord with the design value.

| Parameters   | Injection Voltage (kV) | Injection Dose (cm⁻²) | Arc Current (A) | Bias Voltage (V) | Duty Cycle (%) | Beam (mA) | N₂ Flux (sccm) | Working Pressure (Pa) |
|--------------|------------------------|-----------------------|-----------------|------------------|----------------|-----------|----------------|-----------------------|
| 1st Ti⁺ injection | 8                      | 3 × 10¹⁶              | /               | /                | /              | /         | /              | 3 × 10⁻³               |
| 2nd Ti⁺ injection | 12                     | 3 × 10¹⁶              | /               | /                | /              | /         | /              | 3 × 10⁻³               |
| Ti layer     | /                      | /                     | 100             | −200             | 90             | 550       | 0              | 3 × 10⁻³               |
| TiN layer    | /                      | /                     | 100             | −200             | 90             | 600       | 22             | 8 × 10⁻³               |

Figure 1. SEM image of TiN/Ti coating crossing structure.
2.2. Impact Wear Experiment

A kinetic-controlled cycling impact device was designed as shown in Figure 2. The rightward movement of the damping punch is controlled by a coil motor, which is unbounded with the impact block. The impact block is in contact with the damping punch without force until the coil motor is activated. Then, the impact block and the damping punch are accelerated together towards the right, driven by the coil motor. When achieving the maximum velocity \( V_1 \), the impact block separates from the damping punch and continues to move at the speed of \( V_1 \). The damping punch is hauled back by the coil motor, waiting for the next movement statically at the far left. The ball fastened on the right of the impact block impacts the surface of the sample and rebounds at an inverted velocity \( V_2 \). It gradually slows down until it stops and stays in contact with the damper. It is not stressed by any specific device. The coating sample is fixed to the right-most fixture. All the components of the device were mounted on a fixed base, which was approximately 800 mm long. The impact kinetic energy was controlled by adjusting the mass \( (m) \) and velocity \( (V_1) \) of the impact block separately. During the process of each impact, the contact force and velocity were recorded by the sensors in real-time [13]. The main experiment parameters of the device were as follows: the mass of the impact block was 0–10 g, the impact speed \( V_1 \) was 50–300 mm/s, the impact frequency was 1–15 Hz, the sampling frequency of the contact force was \( 10^3–10^5 \) Hz, and the sampling frequency of velocity was 1000–8000 Hz.

![Figure 2. Schematic illustration of the velocity-controlled impact test.](image)

The Si₃N₄ ceramic balls (offered by Shanghai Institute of Ceramics, Shanghai, China) with a radius of 1.19 mm were used in this study due to their hardness (~21 GPa). The distance between the ball and sample was approximately 20 mm. In actual working conditions, the components would be subject to impacts of varying degrees of energy, so three different cycles were set in the experiment. In order to investigate the evolution law of impact wear damage, four different impact cycles were set. The total mass of the impact block and the ball was 215 g and remained nearly unchanged during each impact cycle. Specific experimental parameters are shown in Table 2. The impact wear zones were observed using a 3D optical microscope and scanning electron microscope (SEM).

| Impact Velocity (mm/s) | Kinetic Energy (mJ) | Impact Cycle |
|------------------------|--------------------|--------------|
| 60 ± 0.364             | 0.39 ± 0.005       | 1⁰           |
| 120 ± 0.991            | 1.55 ± 0.026       | 1⁰           |
| 180 ± 1.164            | 3.48 ± 0.046       | 1⁰           |

2.3. Numerical Simulation

In order to analyze the failure mechanism of impact wear, ABAQUS version 6.13 was used to develop 2D models and to calculate the stress field of multilayer TiN/Ti coatings under the single impact by the Si₃N₄ ceramic ball at a velocity of 180 mm/s. The ceramic ball was modeled as a rigid sphere with a radius of 1.19 mm and a density of 3200 kg/m³. In order to keep the same impact energy as that in the experiment, the initial impact velocity of the ceramic ball was 17.56 m/s.
The coating was modeled as an alternately superimposed structure of two TiN layers and two Ti layers. The total thickness of the coating was 10.81 µm, and the thickness ratio of TiN and Ti layer was 9:1, which is the same as that of the deposited coating.

The TiN layers were modeled as an elastic material. The Ti layer and Ti6Al4V titanium alloy substrate were modeled as an elastic–plastic strain hardening material. The parameters of these materials [14] are detailed in Table 3. The ceramic ball was set as the triangular axisymmetric element (CAX3) composed of more than 80,000 elements. The TiN layer, Ti layer, and Ti6Al4V titanium alloy were all set as four-node axisymmetric elements with reduced integration (CAX4R) and composed of more than 150,000 elements in total. To improve the calculation precision, the meshes in the impact region were refined. Due to the MEVVA process before the coating deposition, the adhesion strength between the coating and substrate is quite high. Therefore, the coating was assumed to be perfectly bonded to the substrate in the numerical model [15].

| Material         | Ti6Al4V | Ti  | TiN | Si3N4 |
|------------------|---------|-----|-----|-------|
| Density (kg/m³)  | 4428    | 5000| 5220| 3200  |
| Elastic modulus (GPa) | 110   | 100 | 400 | -     |
| Poisson’s ratio  | 0.31    | 0.27| 0.25| -     |

### 3. Results and Discussion

#### 3.1. Dynamic Mechanical Response

The 3D morphology of impact wear area on TiN/Ti coatings is shown in Figure 3 inlet (a). The wear area is close to a hemispherical shape. The profile of the cross-section (A-A) is approximately arc-shaped, as seen from the Figure 3 inlet (b). Deformation occurred in this contact area of the coating/substrate system under repeated impact. Figure 3 shows the wear depth (defined as \( h \)) of deformations in the wear area of the TiN/Ti coatings under the impact of different velocities and cycles by the hard Si3N4 ceramic ball. When the impact velocity is 60 mm/s, the wear depth increases from 1.71 µm in \( 10^1 \) cycles to 2.63 µm in \( 10^4 \) cycles, varying relatively smoothly. As impact velocity increases to 120 mm/s, the kinetic energy of a single impact is three times higher than that of an impact at 60 mm/s. The wear depth is also getting higher with the value of 4.34 µm at \( 10^1 \) cycles and 6.53 µm at \( 10^4 \) cycles. At an impact velocity of 180 mm/s, the maximum wear depth of 10.26 µm is reached at \( 10^4 \) cycles. The wear depth increases with the velocities and impact cycles.

![Figure 3. Wear depths of wear zones on coating/substrate systems.](image-url)
The equivalent increasing rate of depth (IRD) is put forward to analyze the increasing rate of depths with increasing cycles. IRD is calculated with the following formula:

\[
IRD_i = \frac{h_i - h_{i-1}}{10^i - 10^{i-1}}
\]

where \(IRD_i\) is the average deformation rate of depths from the \(10^{i-1}\)th to \(10^i\)th cycle \((i = 1, 2, 3, 4)\), and \(h_i\) is the remaining wear depth after \(10^i\) cycles of impact. The calculated results are shown in Figure 4. When the impact velocity is 60 mm/s, IRD decreases from 0.17 µm/cycle at stage (i) to \(5.94 \times 10^{-6}\) µm/cycle at stage (iv). IRDs at higher velocities have the same trend. At stage (i) of different impact velocities, \(IRD_1\) is about 0.43 µm/cycle at the velocity of 120 mm/s, nearly equal to that at 180 mm/s (0.49 µm/cycle), and is approximately three times that observed at 60 mm/s. It means higher impact energy induces a higher deformation rate. As impact cycles increase to \(10^2\), \(IRD_2\) drops a lot compared to stage (i). The impact of the ceramic ball on the sample causes a hardening effect on its surface [16]. The hardness of the sample surface increases, and the ability to resist deformation increases, and so, \(IRD_2\) is greatly reduced. The wear depth increases smoothly after \(10^3\) cycles. At stage (iv), \(IRD_4\) are all below \(1.0 \times 10^{-4}\) µm/cycle. The results above indicate that the wear depth is sensitive to impact velocities and cycles.

Figure 4. The equivalent increasing rate of depths (IRD) in impact zones.

Figure 5 shows the dynamic mechanical responses of substrate/coating systems under different impact velocities and cycles. The contact force is generated when the ceramic ball contacts the coating and then reaches a peak value. Finally, it decreases to zero once the two contacting parts separate from each other. The contact time during each single impact is about 0.55 ms, and it remains almost the same at different impact velocities (60, 120, 180 mm/s, respectively). The dynamic responses including the peak force and contact time possess the same trend as the impact cycles and increase when the impact velocities are constant. This indicates that the mechanical dynamic response is not sensitive to the impact cycle. The peak force of a single impact increases with the impact velocity linearly from 73.30 N at 60 mm/s to 262.26 N at 180 mm/s, as shown in Figure 5 inlet (a). This is easy to understand according to the theorem of impulse. When the object mass and contact time are fixed, the greater the impact velocity, the greater the contact force.
Figure 5. The dynamic mechanical response of coating/substrate system.

The energy dissipated rate (EDR) is adopted in this work to describe the dynamic mechanical response, which is the ratio of dissipated kinetic energy ($K_D$) and the total impact kinetic energy ($K_T$) in the single impact. $K_D$ is calculated as follows:

$$K_D = K_T - \frac{1}{2}mv_2^2$$

where $m$ is the total mass of impact block and the ball, $v_2$ is the rebound velocity of the ball.

The calculated results indicate that EDR remains the same with the increased impact cycles under the same velocity. This is due to almost the same dynamic responses with the increased impact cycles. The 10th impact cycle results at different velocities are depicted in Figure 6. It can be seen that the dissipated energy of each impact at a velocity of 180 mm/s is 1.24 mJ, which is about ten times that observed at 60 mm/s (0.12 mJ). EDR increases from 31.58% to 35.59% with increasing velocities from 60 mm/s to 180 mm/s. Therefore, it can be concluded that the more kinetic energy impact on coatings, the more energy dissipates. Furthermore, EDR also increases slightly with increased impact kinetic energy. The dissipated kinetic energy contains plastic deformation energy, failure energy, and energy consumption of heat, vibration, and sound [17,18]. The failure energy includes the ones that cause the cohesive peeling, adhesive peeling, and the formation of circular crack. According to the results of wear depth, the plastic deformation amount is slightly higher than the energy multiple when an impact effect of great energy is applied to the coating’s surface than when an impact effect of lower energy is applied. In addition, it also generates more cracks (see in Figure 8). Therefore, more energies are dissipated and the EDR is higher as the impact kinetic energy increases.

Figure 6. The absorption/rebound energy and energy dissipated rate with impact velocity.
During the single impact process, as described above, the contact force rises to a peak value, while the Si$_3$N$_4$ ball extrudes into the deepest position of substrate/coating systems and then decreases while the Si$_3$N$_4$ ball is separating from coatings. Therefore, the instantaneous contact stress changes with the contact condition during the whole impact process. To compare contact stress at different velocities and cycles, the peak force ($F_M$) is used to calculate the contact pressure. An assumption is made that the contact force is uniformly distributed in the normal direction on the spherical surface of wear zones in order to simplify the calculation. Thus, the contact stress is considered to be the same and defined as $p$. For example, a point N is on the spherical surface, whose contact force is defined as $F_N$, and the contact stress is $p$. The angle between $F_N$ and $F_M$ is defined as $\theta$. The relation between $p$ and $F_M$ can be referred to by Formula (3). The central angle of the wear arc can be calculated with Formula (4). According to Formulas (3) and (4), the contact stress $p$ can refer to Formula (5).

$$F_M = \int_0^\alpha p \cdot \cos \theta \cdot 2\pi R \sin \theta \cdot Rd\theta$$  \hspace{1cm} (3)

$$\cos \alpha = \frac{R - h}{R}$$  \hspace{1cm} (4)

$$p = \frac{F_M}{\pi(2R - h)h}$$  \hspace{1cm} (5)

Figure 7 shows the maximum instantaneous contact stress at different impact velocities and cycles. The maximum contact stress at $10^3$th impact is 2.61~3.57 GPa and the pressure at the velocity of 120 mm/s is the lowest. However, as the repetitive impact cycle exceeds $10^2$, the maximum values of temporary contact stress at three different impact velocities are all lower than 2.5 GPa, due to the nearly constant dynamic mechanical response and the increasing wear depths. As cycles exceed $10^3$, contact stress is further reduced (to less than 2.0 GPa) but at a slower rate. It is because the major plastic deformation occurs at the former impact stage, and the wear depth’s increasing rate is going down constantly at the latter impact stage according to the results in Figure 4.

![Figure 7](image_url)  
Figure 7. Contact stress of wear zones at $10^i$th cycle ($i = 1, 2, 3, 4$).

3.2. Failure Mechanism

The damage morphologies of the TiN/Ti coatings under cycling impacts with different impact velocities and cycles are shown in Figure 8. There are three kinds of typical damage characteristic phenomena in impact zones, including plastic deformation, peeling (almost adhesive peeling), and circular cracks. From the 3D morphology and 2D profile of cross-sections (in Figure 3a,b), the impacted
zone appears to be a spherical surface and is the result of the coordinating plastic deformation of the substrate/coating system. The plastic deformation occurs in all impact velocities and cycles. When TiN/Ti coatings are impacted with a low kinetic energy (velocity of 60 mm/s) during $10^1$ and $10^2$ impact cycles, only plastic deformation occurs. As the impact cycle increases to $10^3$, peelings on spherical surfaces begin to appear. The circular cracks surrounding damaged zones can be seen after $10^4$ cycles. When impact velocity increases to 120 mm/s, circular cracks occur in cycles from $10^3$ to $10^4$. Peelings on coating surface start to occur from $10^2$ cycles. All three damage phenomena, plastic deformation, peeling, and circular cracks, can be seen throughout $10^1$ to $10^4$ cycles in the velocity condition of 180 mm/s.

![Figure 8. Microscope morphologies of damaged zone on the surface of TiN/Ti coatings under repetitive impacts.](image)

The contact stress field distribution of the cross-sections as the ball reaches the deepest position calculated by ABAQUS was shown in Figure 9a. In the central zone of the impact area (Detail A in Figure 9) and the intermediate zone (Detail B in Figure 9), tensile stresses exist in hard TiN layers and compressive stresses exist in both sides of the interfaces, as shown in Figure 9b,c,e,f. A large stress gradient forms in the middle regions of these two different stress areas, regions which tend to be the source of more damage. Several peelings in the impact area can be seen from Figure 9d. The high stress gradient aroused by cycling impact resulted in the fatigue peelings of coatings [19]. Tensile stresses (as shown in Figure 9h) appear on the upper part of hard TiN layers in a circular contacting area, as shown in Detail C in Figure 9. This cycling tensile stress in hard layers under cycling impacts induces fatigue-related circular cracks in hard coatings. These circular cracks can be seen from the damage morphology of the edge impact area, as shown in Figure 9g,j. In addition to the circular cracks, peelings are also displayed, which are caused by the cycling great stress gradient seen in Figure 9i. Therefore, the failure mechanisms of multilayer TiN/Ti coatings under cycling impacts include fatigue peelings and circular cracks. They are induced by the high stress gradient and the cycling tensile stresses in the hard layer and interfaces between layers, respectively.
Figure 9. Stress distribution of multilayer TiN/Ti coating under impact: (a) the contact stress field distribution of the cross section; (b) the stresses in area A; (c) the detail in area A; (d) microscope morphology in area A; (e) the stresses in area B; (f) the detail in area B; (g,j) microscope morphologies in area C; (h,i) the stresses in area C.

4. Conclusions

The impact wear behavior of four-layer TiN/Ti coatings was evaluated with a kinetic-controlled cycling impact test under different impact velocities and cycles. Impact dynamic response and damage failure mechanisms of coatings under cycling impact were investigated. The following conclusions have been drawn:

- The wear depth of coatings increases with impact cycles at a gradually decreasing rate. The rate of depth increase is below $10^{-4}$ µm/cycle after $10^3$ cycles due to the decreasing contact stress with the increased impact cycles.
- The contact time keeps almost constant (about 0.55 ms) during a single impact under different impact velocities and cycles. Peak forces also remain unchanged with increasing cycles under the same velocity and increase with impact velocities linearly, reaching a maximum value of 262.26 N at 180 mm/s. The energy dissipated rate (EDR) remains constant with different impact cycles and increases smoothly with impact velocities from 31.58% at 60 mm/s to 35.59% at 180 mm/s.
- Two failure mechanisms are found in the impact zones of the coating. These are peeling and circular cracks. Peelings are induced by cycling high stress gradients in hard layers and interfaces between hard layers and interlayer/adhesive layers. Circular cracks are caused by cycling tensile stresses in the form of fatigue at the edge of impacted pits.

Author Contributions: Conceptualization, W.H.; Investigation, W.X.; Methodology, X.C.; Project administration, W.H.; Software, W.X.; Writing—original draft, X.C.; Writing—review and editing, X.C. and W.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Science and Technology Major Project (2017-VII-0012-0107).

Acknowledgments: The College of Nuclear Science and Technology at Beijing Normal University supported the coating deposition facilities.

Conflicts of Interest: The authors declare no conflict of interest.
References

1. Proudhon, H.; Savkova, J.; Basseville, S.; Guipont, V.; Jeandin, M.; Cailletaud, G. Experimental and numerical wear studies of porous Reactive Plasma Sprayed Ti–6Al–4V/TiN composite coating. Wear 2014, 311, 159–166. [CrossRef]

2. Yang, Q.; McKellar, R. Nanolayered CrAlTiN and Multilayered CrAlTiN–AlTiN coatings for solid particle erosion protection. Tribol. Int. 2015, 83, 12–20. [CrossRef]

3. Borawski, B. Multilayer Erosion Resistant Coatings for the Protection of Aerospace Components; Pennsylvania State University: Centre County, PA, USA, 2011.

4. Zhu, M.; Cai, Z.; Lin, X.Z.; Ren, P.D.; Tan, J.; Zhou, Z. Fretting wear behaviour of ceramic coating prepared by micro-arc oxidation on Al–Si alloy. Wear 2007, 263, 472–480. [CrossRef]

5. Liu, W.; Chu, Q.; He, R.; Huang, M.; Wu, H.; Jiang, Q.; Chen, J.; Deng, X.; Wu, S. Preparation and properties of TiAlN coatings on silicon nitride ceramic cutting tools. Ceram. Int. 2018, 44, 2209–2215. [CrossRef]

6. Knotek, O.; Bosscherhoff, B.; Schrey, A.; Leyendecker, T.; Lemmer, O.; Esser, S. A new technique for testing the impact load of thin films: The coating impact test. In Metallurgical Coatings and Thin Films 1992; Elsevier: Amsterdam, The Netherlands, 1992; pp. 102–107.

7. Bantle, R.; Matthews, A. Investigation into the impact wear behaviour of ceramic coatings. Surf. Coat. Technol. 1995, 74–75, 857–868. [CrossRef]

8. Lawes, S.D.A.; Hainsworth, S.V.; Fitzpatrick, M.E. Impact wear testing of diamond-like carbon films for engine valve-tappet surfaces. Wear 2010, 268, 1303–1308. [CrossRef]

9. Abdollah, M.F.B.; Yamaguchi, Y.; Akao, T.; Inayoshi, N.; Miyamoto, N.; Tokoroyama, T.; Umehara, N. Deformation–wear transition map of DLC coating under cyclic impact loading. Wear 2012, 274–275, 435–441. [CrossRef]

10. Chen, Y.; Cheng, T.; Nie, X. Wear failure behaviour of titanium-based oxide coatings on a titanium alloy under impact and sliding forces. J. Alloy. Compd. 2013, 578, 336–344. [CrossRef]

11. Bouzakis, K.D.; Charalampous, P.; Skordaris, G.; Dimofte, F.; Ene, N.M.; Ehinger, R.; Gardner, S.; Modrzejewski, B.S.; Fett, J.R. Fatigue and adhesion characterization of DLC coatings on steel substrates by perpendicular and inclined impact tests. Surf. Coat. Technol. 2015, 275, 207–213. [CrossRef]

12. Xu, W.; He, G.; Cai, Z.; Liao, B.; Cao, X.; He, W. Damage analysis of TiN/Ti coatings under cyclic impact loading with hard particles. China Surf. Eng. 2017, 30, 28–35. (In Chinese)

13. Lin, Y.; Cai, Z.; Chen, Z.; Qian, H.; Tang, L.; Xie, Y.; Zhu, M. Influence of diameter–thickness ratio on alloy Zr–4 tube under low-energy impact fretting wear. Mater. Today Commun. 2016, 8, 79–90. [CrossRef]

14. Hassani, S.; Klembberg-Sapieha, J.E.; Bielawski, M.; Beres, W.; Martinu, L.; Balazinski, M. Design of hard coating architecture for the optimization of erosion resistance. Wear 2008, 265, 879–887. [CrossRef]

15. Zhang, H.; Li, Z.; He, W.; Liao, B.; He, G.; Cao, X.; Li, Y. Damage evolution and mechanism of TiN/Ti multilayer coatings in sand erosion condition. Surf. Coat. Technol. 2018, 353, 210–220. [CrossRef]

16. Wang, Y.; Zhou, Z. An investigation of impact wear and wear mechanism of TC4 alloy. Lubr. Eng. 2009, 34, 1–4. (In Chinese)

17. Cai, Z.; Guan, H.; Chen, Z.; Qian, H.; Tang, L.; Xie, Y.; Zhu, M.H. Impact fretting wear behavior of 304 stainless steel thin-walled tubes under low-velocity. Tribol. Int. 2017, 105, 219–228. [CrossRef]

18. Uetz, H.; Föhl, J. Wear as an energy transformation process. Wear 1978, 49, 253–264. [CrossRef]

19. Bouzakis, K.D.; Maliaris, G.; Makrimalakis, S. Strain rate effect on the fatigue failure of thin PVD coatings: An investigation by a novel impact tester with adjustable repetitive force. Int. J. Fatigue 2012, 44, 89–97. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).