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Low velocity impact wear behavior of MoS_2/Pb nanocomposite coating under controlled kinetic energy

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ABSTRACT

In this study, low velocity impact tests were performed to MoS_2/Pb nanocomposite coating and its substrate (304-stainless steel, for comparison). The machine is controlled based on kinetic energy and can achieve dynamic response during the tests. The MoS_2/Pb coating exhibits better impact wear resistance, as shown by its favorable dynamic response. The energy absorption ratio evolution of MoS_2/Pb coating indicates there were several impact damage forms during the tests, which was relevant to varied dominant impact damage mechanisms. In addition, tests with varied impact conditions were conducted, and distinct results were obtained, revealing the effects of tests parameters. Moreover, comparative analysis between values obtained from the Hertz theory and the measured revealed that the yield strength of MoS_2/Pb coating was approximately 686.5 MPa, and the substrate was always under elastoplastic deformation although its impact kinetic energy was the lowest. The low velocity impact morphology was characterized by fatigue delamination because of the shearing stress in the subsurface.

1. Introduction

Coatings improve superficial properties of materials to help protect the matrix against material degradation and failure of mechanical components in various fields [1–3]. In addition to natural properties, coatings perform differently because of their diverse structures (e.g. monolayer, multilayer, and modulation period). And it has been reported [4] that the bonding layer affects the protection of the substrate from deformation. Erosion, which is another impact issue, has also attracted much attention. Multilayered PVD coatings, in particular Ti/TiN (1:1), suppress crack initiation and have exhibited good wear resistance because of the high hardness of the TiN layer [5]. Meanwhile, the coordinated deformation between the coating and substrate remarkably influences the performance of coated specimens [6,7].

A variety of engineering components are under ball-to-flat surface contacts, which are periodically separated and contacted for several times. The cyclical impacts can eventually degrade the component's surface layers whether they are natural oxides, or coatings, which dramatically increases the tendency of these contacting surfaces to cold-welding [8]. And MoS_2 coatings are widely used to reduce the wear of contact interfaces and extend service life. In the drilling system of space exploration, there are several impact contact interfaces, under the influence of coupled motion of impact spindle [9]. In other fields, the application of MoS_2 coatings are suitable to the requirements of lubrication and protection under clearance fit, which results in vibration and impact between the interfaces [10]. In these cases, the coupling of impact wear and other forms of damage makes the failure mechanisms more complicated. Therefore, researches of impact resistance and characteristics of MoS_2 coating help to achieve further understanding of its damage behavior in applications as mentioned above. However, the MoS_2 crystal is prone to be attracted by H_2O to MoO_3, which causes higher friction coefficient [11]. Nevertheless, the tribological properties of MoS_2 coating can be improved by doping with another element. And Pb is one of the most frequently used metallic dopants, resulting in enhanced wear resistance of MoS_2/Pb [12].

For coated surfaces suffering from cyclic dynamic load, impact test is a reasonable method to study the impact behavior and properties of coatings [13–18]. These impact tests are mainly conducted with normal ball-to-flat contact, and the control condition of machine is only measured by maximum normal impact forces. Robinson [19] showed that differences in impactor mass do not significantly affect impact performance. Such concepts might be the foundation for simplifying the dynamic loads into the maximum impact forces. Abdollah et al. [20] concluded that maximum normal impact load affected the material loss most. Additionally, three characteristic failure zones of hard coatings were found, which were relevant with the position on the wear scar [21]. These experimental investigations showed that the present methods used to characterize performance, such as visual detection (SEM, 3D contour, etc.) and self-defined features [22,23], are conventional and limited. The impact test based on force is not the only controlled mode. It has been reported [24] that the volume/depth loss of coatings is enlarged when impact time increases under the same maximum force, which demonstrates that the force-controlled mode has

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Table 1
Deposition parameters of MoS2/Pb coating.

Parameters	MoS_2/Pb
Working pressure (Pa)	1.33×10^{-3}
Bias voltage (V)	−50
Target current of MoS_2 (A)	0.8
Target current of Pb (A)	0.3

potential flaws. A recently presented reasonable controlled mode is based on impact kinetic energy $\boldsymbol{E_i}$ [25–27]. This method enables the real-time acquisition of dynamic response, including details of energy conversion and waveform of impact force, during the impact process.

In this study, MoS_2/Pb nanocomposite coating was deposited on 304 stainless steel and tested with low velocity impact based on controlled $\boldsymbol{E_i}$. Then, the impact behavior and features of the coating were determined according to the dynamic responses. For comparison, a separate substrate was also tested. The individual effects of impact velocity $\boldsymbol{v_i}$ and impact mass $\boldsymbol{m}$, which determines $\boldsymbol{E_i}$, were investigated by variable-controlling tests to determine which parameter is more important to the impact wear. Furthermore, tests with different $\boldsymbol{m}$ values under the same $\boldsymbol{E_i}$ were also conducted to obtain a comprehensive understanding of the controlled mode.

2. Experimental method

2.1. Materials

The 304-austenitic stainless steel (30 mm × 30 mm × 2 mm) was used as substrate, and the MoS_2/Pb nanocomposite coating was deposited by an unbalanced magnetron sputtering system (UDP-650). The system had two MoS_2 targets, namely, one Ti target and one Pb target, and the substrates rotated between the targets. Prior to deposition, the vacuum chamber was evacuated to 1.33×10^{-3} Pa, and then the 304-stainless steel flats were sputter-cleaned by Ar^+ ion for 30 min, with a bias of −500 V. Ti target was used to deposit an interlayer of approximately 200 nm, which improved the adhesion between the coating layer and the substrate. The specific deposition parameters are presented in Table 1. In addition, the GCr15 steel ball was used as an impactor.

The cross-section image of the MoS_2/Pb composite coating was performed by scanning electron microscopy (SEM, JSM-6610), and electron probe micro analyzer (EPMA, JXA-8230) was used to detect the elements distribution of the as-deposited coating. The compositions of coating were analyzed by energy-dispersive X-ray spectroscopy (EDX, EDAX-7760/68M) and X-ray photoelectron spectroscopy (XPS, ESCALAB-250Xi) with Al K-Alpha radiation. Besides, the hardness and elastic modulus were measured by a Nano-indenter (MTS Nano Indenter G200) using a Berkovich diamond tip. The maximum indentation depth was 200 nm, which was less than 10% of the coating thickness to minimize the effect of the substrate.

Table 2
Experimental parameters (impact number N = 10^4).

Test numbers	Flat specimen	Diameter of impactor (mm)	Impact mass (g)	Impact velocity (mm/s)
1#–4#	MoS_2/Pb composite	9.525	107	30, 42, 60, 90
5#–6#	coating	9.525	234, 448	30
7#–8#		4.763, 2.381	107	30
9#–12#	304 stainless steel	9.525	107	30, 42, 60, 90

2.2. Impact tests

The tribological performances were evaluated by a low velocity impact wear machine (Fig. 1a) [25]. This apparatus was designed to achieve repeated impingement, and the controlled mode was based on the $\boldsymbol{E_i}$ instead of impact force. When the test was started, the voice coil motor moved under sine/cosine model, which was controlled by PC program. Then, the damping punch was motivated and drove the active cell. The motion of the active cell was identified as uniform after the cell separated from the damping punch, since the dynamic friction coefficient of linear guide was less than 0.006. The active cell rebounded after the collision, and was ready for the next impact cycle when the damping punch was reconnected. During this process, the velocity of the active cell was measured by a displacement sensor and divided in two parts, namely, the impact ($\boldsymbol{v_i}$) and rebound ($\boldsymbol{v_r}$) velocities. And the energy absorption ratio can be calculated by Eq. (1), in which the $\boldsymbol{E_r}$ represents the kinetic energy of the active cell after impact. Meanwhile, as another dynamic response of test results, the waveform of impact force was determined by a piezoelectricity force sensor, including peak impact force $\boldsymbol{F_{max}}$ and impact duration $\boldsymbol{t}$.

$$\delta = \frac{E_i - E_r}{E_i} \tag{1}$$

The flat specimen was tested with normal impact under room temperature. The substrate was tested by turning the coated flats over to investigate the coating–substrate system with different superficial properties and evaluate the effects of structure to the system (Fig. 1b). Prior to the tests, the flats and impactors were cleaned by anhydrous ethanol in an ultrasonic bath. Then, four various $\boldsymbol{E_i}$ were applied to the flat specimen by adjusting the $\boldsymbol{v_i}$. And the active cells with different mass $\boldsymbol{m}$ were used at $\boldsymbol{v_i}$ = 30 mm/s to reach the same $\boldsymbol{E_i}$ as mentioned above. Meanwhile, the impact performance under different diameter $\boldsymbol{d}$ of the impactor was also investigated. This variable parameter could lead to diverse levels of contact stress on the interface between the flat and impactor. The specific test numbers and parameters are shown in Table 2, and each test was repeated twice.

The surface morphology of the impact scars was observed by scanning electron microscopy (SEM, JSM-6610) after the tests. A 3D optical microscope (3D-OM, NPFLEX) was used to detect the cross-section

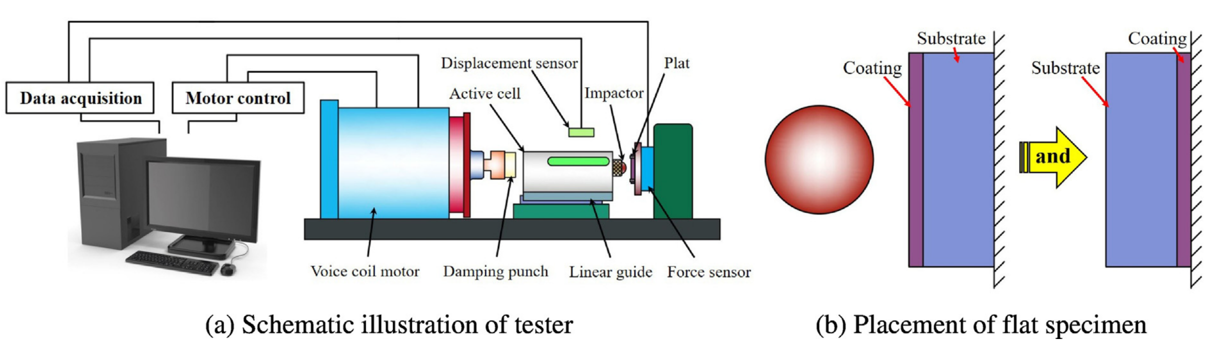

Fig. 1. Details of the impact tester.