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Deformation–wear transition map of DLC coating under cyclic impact loading

Mohd Fadzli Bin Abdollah[a,*], Yuto Yamaguchi[a], Tsuyoshi Akao[b], Naruhiko Inayoshi[c], Nobuyuki Miyamoto[c], Takayuki Tokoroyama[a], Noritsugu Umehara[a]

[a] *Department of Mechanical Science and Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan*
[b] *Technology Planning Department, DENSO Corporation, 1-1 Showa-cho, Kariya-shi, Aichi 448-8661, Japan*
[c] *Materials Engineering R&D Department, DENSO Corporation, 1-1 Showa-cho, Kariya-shi, Aichi 448-8661, Japan*

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ABSTRACT

A new deformation–wear transition map of hydrogen-free amorphous carbon coating (commonly known as Diamond-Like Carbon (DLC) coating) on tungsten high speed steel (SKH2) substrate under cyclic impact loading has been proposed to clarify the interactions of the operating parameters, deformation and wear. The study was carried out using an impact tester, under lubricated conditions over a wide range of impact cycles, and applied normal loads. SKH2 discs were coated with thin DLC films using a Physical Vapor Deposition (PVD) method. Tungsten (W) was used as an interlayer material. The DLC coated disc was impacted repeatedly by a chromium molybdenum steel (SCM420) pin. All impact tests were conducted at room temperature. It has been suggested that the deformation–wear transition map is an easy way to illustrate the impact wear mechanisms of DLC coating, as shown by its transition zones. Initially, the DLC coating only follows the plastic deformation of the substrate until several impact cycles. Then, a suppression of plastic deformation of the substrate is taking place due to the decreasing contact pressure with impact cycles to the yield point. Wear of the DLC coating becomes dominant when the critical limit of maximum normal impact load and impact cycles is exceeded. From experimental observations, some degradation of the DLC coating occurs within the wear zone.

1. Introduction

DLC has attracted great attention for many applications due to its tremendous properties, such as high hardness, thermal stability, low friction coefficient, and good chemical inertness. Furthermore, the DLC film showed an excellent wear resistance in dry and water- or oil-lubricated conditions [1]. The use of DLC coating, on the impact surfaces of components, provides high levels of protection against surface damage.

The concept of a 'wear map' was first discussed by Tabor [2], and was inspired by the pioneering work of Frost [3] on 'deformation maps'. The development of deformation–wear transition map is a useful way to study and predict the transition of deformation to wear of one material impacting against another at different loads and cycles. Furthermore, the locations of the transition zones within the operating parameters are important, in order to design engineer less component failures occurring prematurely.

Generally, the construction of transition maps follows two routes [4,5]. One is empirical: data from experiments are plotted on suitable axes and identified by wear rate or observation and boundaries are drawn to separate classes of behavior. The other route is that of physical modeling: model-based equations, describing the wear rate caused by each mechanism, are combined to give a map showing the total rate, and the field of dominance of each. However, only the empirical approach is used in this study.

The wear transition maps specific to certain materials, such as ceramics [6], grey cast iron [7], magnesium alloy [8], brass alloy [9], silicon nitrite [10], have been developed extensively for a decade. All the transition maps, which appear in the above studies, were constructed using either a physical modeling or an empirical approach based on the sliding test data. However, in this century, there is still no development of deformation–wear transition map of the DLC coating under cyclic impact loading. Therefore, the aim of this study is to propose a new deformation–wear transition map of DLC coating based on variations of maximum normal impact loads and impact cycles. After a short description of the impact test used in this study, the construction of the deformation–wear transition map will be presented using experimental data and observations. The transition map of DLC coating, under cyclic impact loading,

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* Corresponding author. Tel.: +81 52 789 2788; fax: +81 52 789 2788.
E-mail addresses: mohdfadzli@utem.edu.my (M.F.B. Abdollah), yamaguchi@ume.mech.nagoya-u.ac.jp (Y. Yamaguchi), TSUYOSHI_AKAO@denso.co.jp (T. Akao), NARUHIKO_INAYOSHI@denso.co.jp (N. Inayoshi), NOBUYUKI_MIYAMOTO@denso.co.jp (N. Miyamoto), tokoroyama@mech.nagoya-u.ac.jp (T. Tokoroyama), ume@mech.nagoya-u.ac.jp (N. Umehara).

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tends to focus on the description of its impact wear mechanisms and the transition between them.

2. Experimental method

2.1. Materials

The SKH2 disc was used as a substrate, whilst SCM420 pin was used as an impactor. The diameter of the disc and the pin were 10 mm and 2 mm, respectively (as shown in Fig. 1). All DLC films were deposited onto the SKH2 substrate using a PVD method; where W was used as an interlayer material. The film thickness h_c is approximately 2.97 μm. The average surface roughness R_a of the as-deposited DLC coating is approximately 18.63 nm, which was measured by Atomic Force Microscopy (AFM). Material properties are listed in Table 1.

2.2. Impact testing

The impact test was performed using two self-developed impact testers, as shown in Fig. 2. The horizontal impact tester was used for more than 10^2 impact cycles, with a frequency of 10 Hz; and a drop-weight impact tester was used for the low impact cycles.

The impact test rig was designed to impact a DLC coated disc with a SCM420 pin for numerous impacts. Prior to the impact test, both disc and pin were cleaned using acetone in an ultrasonic bath. The DLC coated disc was repeatedly impacted at a 90° inclination at room temperature. Several different maximum normal impact loads were applied to the DLC coated disc via a spring system for the horizontal impact tester. Meanwhile, the maximum normal impact load of the drop-weight impact tester could be increased by adding an impactor mass m. It has been reported that the impactor mass does not significantly affect impact performances (deformation and wear) [11,12]. The applied load was observed by a load cell.

The surface morphology of the affected area on the DLC coating, as well as on the counterpart material, was observed by AFM, Field Emission Scanning Electron Microscopy (FE-SEM), and Energy Dispersive X-ray Spectroscopy (EDS). In addition, the Focused Ion Beam (FIB) was used to mill the tested sample, in order to examine the cross section of the DLC coating on the SKH2 substrate.

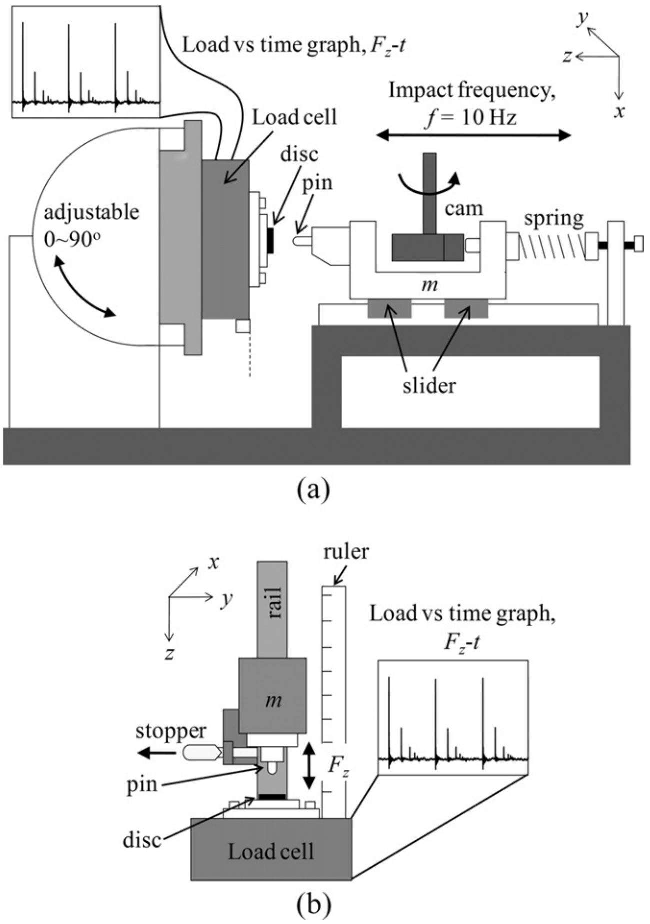

Fig. 2. Schematic illustration of the impact tester: (a) horizontal impact tester and (b) drop-weight impact tester.

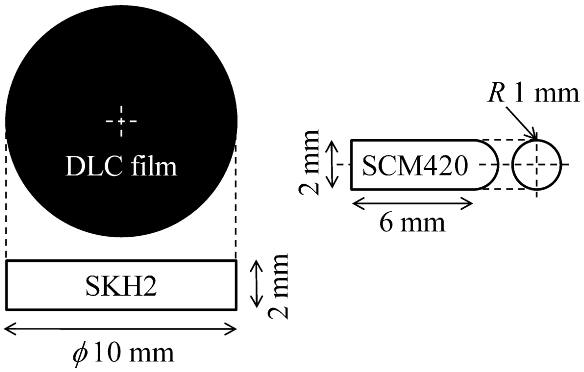

Fig. 1. Dimensions of the DLC coated disc and the SCM420 pin.

Table 1
Material properties of the DLC, SKH2 substrate and SCM420 pin.

Properties	DLC	SKH2	SCM420
Young modulus, E (GPa)	251	378	295
Poisson's ratio, ν	0.3	0.3	0.3
Hardness, H (GPa)[a]	17.14	9.80	7.43
Yield strength, Y (GPa)[b]	6.12	3.50	2.65

[a] From the nanoindentation test.
[b] $Y = H/2.8$.

2.3. Residual impact crater volume/depth

The raw data collected included the measurements of the residual impact crater volume and its depth/radius. The depth h_r and radius a_r of the residual impact crater of the DLC coating were measured directly from a cross-sectional AFM topography image. The cross-sectional image, parallel to the y-axis, was taken at the center of impact crater, as shown in Fig. 3. In order to calculate the residual impact crater volume, raw data from the AFM was exported to OriginPro 8.1. An illustration of how the residual impact crater volume was calculated is shown in Fig. 3. The raw data of x-axis were discrete to n cross-sections with the thickness of Δx. The surface area A of each cross-section was determined using the integration method function in OriginPro 8.1. The residual impact crater volume V_r is determined using the following equation:

$$V_{\mathrm{r}} = \sum_{j=1}^{n-1} (A \times \Delta x)_j \tag{1}$$

2.4. Transition of contact pressure

In this present paper, the loading conditions are beyond the elastic limit. Therefore, Hertz's contact calculation theory is not strictly applicable. However, Hertz's calculation was applied using the following assumption as one index of contact pressure [13]: