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Combinative influence of impact and pressing forces on coating failure behaviour

J.F. Su [a], X. Nie [a,*], T. Mulholland [b]

[a] Department of Mechanical, Automotive, & Materials Engineering, University of Windsor, Windsor, Ontario N9B 3P4, Canada
[b] General Motors Company, Global Dies & Press Center, Warren, MI 48090, United States

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ABSTRACT

In this work, a ball-on-plate impact fatigue test was proposed as an experimental technique to investigate the failure behaviour of coating–substrate systems under simulated stamping force conditions. Each impact cycle consisted of an impact force and a pressing force which could be adjusted by changing the distance between the impact ball and the plate surface and by regulating air pressure in the air cylinder of the impact tester, respectively. Two PVD (CrN and TiAlN) and one CVD (TiC) coatings on D2 substrates were tested at combinations of different impact/pressing loads (i.e., 200 N/400 N, 400 N/400 N and 600 N/400 N) for 10,000 cycles. It was found that the sizes of the impacted craters were linearly increased with the impact forces and were more dependent on the substrate than the coatings. The possible failures of the tested coatings included not only cohesive and adhesive failure modes but also fatigue cracking. The CrN coating was the best against the failures at all load combinations. While the TiC coating only showed a small degree of chipping after the test at the highest impact/pressing load, all cohesive and adhesive failures and fatigue cracks could be observed on the TiAlN coating even at the lowest impact/pressing load condition.

1. Introduction

Since physical and chemical vapor deposition (PVD/CVD) coatings usually have a much higher hardness and resistance of wear than electroplated or electroless coatings and nitrided steels, hard coatings have been considered as necessary top layers of a wide variety of mechanical components to battle the wear problems. The hard coatings are growingly being used to improve the tribological properties and wear resistance of various tools for metal cutting, forming and stamping [1]. For instance, due to the increasing use of advanced high strength steels, die wear prevention has become an important issue in the stamping of automotive parts. The hard coatings have a trend to be used as much-needed protective top layers on surfaces of stamping dies thereby to extend the tool life and improve the quality of the stamped products [2–6]. The coatings must have a good adhesion to the base material to withstand the high loads and shearing forces without chipping or peeling, and low friction coefficient to reduce wear [7,8]. The coating fatigue strength is also one of the critical parameters that have to be taken into account during the selection of the appropriate coating/substrate system for applications such as stamping. Therefore, mechanical properties of hard coatings to be concerned include not only hardness, residual stress and adhesion, but also cohesion and fatigue failure behaviour.

Most practical adhesion test methods such as pressure-sensitive tape test, pull-off, scratch and indentation involve static or quasi-static elastoplastic loading [9,10]. For applications that dynamic repetitive loadings are applied, a ball-on-plate impact test was first introduced to evaluate the adhesive and cohesive failures of hard coatings [11,12]. Bantle and Matthews indicated that three failure zones are involved in the impact indent: a central zone with cohesive failure, an intermediate zone with cohesive and adhesive failures and a peripheral zone with circular cracks failure plus pilling up of the material [13]. Knotek et al. [11] and Bouzakis et al. [14,15] showed that the degradation of the coating induced by repetitive dynamic impact is a fatigue behaviour. However, the previous research work did not carefully look into the combinative loading process of impact force and pressing force. The impact and pressing force combination are actually the cases during the stamping. Thus, in the present work, three different combinations of impacting/pressing loads were used to evaluate three types of hard coatings, CrN, TiAlN and TiC, during the ball-on-plate impact tests. The selection of the coatings was based on their good performance in an industrial auto stamping plant. The influence of the impact forces on the crater sizes of the coated and uncoated substrates and failure behaviour of the coating/substrate systems were then discussed.

2. Experimental details

2.1. The impact tester

The schematic of the impact tester is shown in Fig. 1. A hardened SAE 52100 steel ball of 10 mm in diameter is driven by a two-way stroke air

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* Corresponding author. Tel.: +1 519 253 3000x4148; fax: +1 519 973 7007.
E-mail address: xnie@uwindsor.ca (X. Nie).

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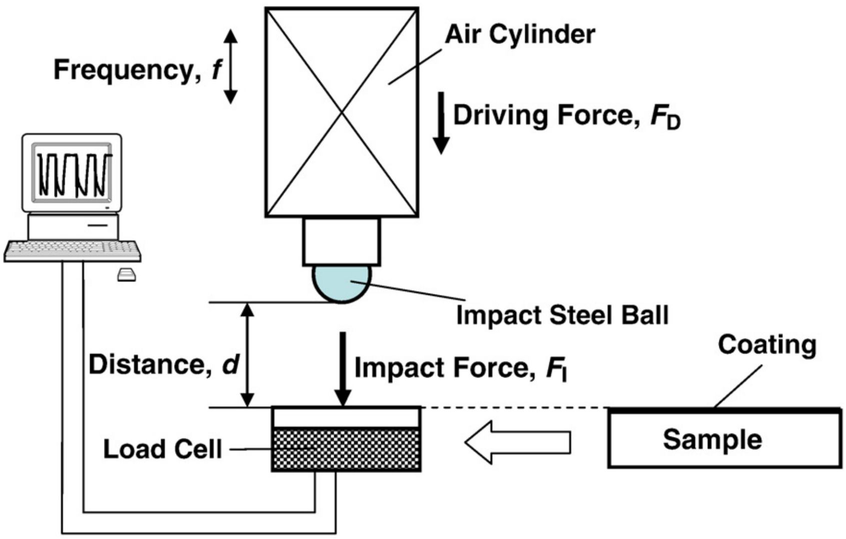

Fig. 1. Schematic of the impact tester.

cylinder with compressed air. The quasi-static driving force F_D was assumed to be constant for a given air pressure, neglecting friction force. With a fixed impact mass m, the relationship between distance d and traveling time of the ball to the sample surface t is

$$d = \frac{1}{2}at^2 = \frac{1}{2}\frac{F_D + mg}{m}t^2 \quad (1)$$

The velocity of impact mass reaching sample surface, v is given by

$$v = at = \frac{F_D + mg}{m}\sqrt{\frac{2md}{F_D + mg}} = \sqrt{2d\left(\frac{F_D}{m} + g\right)} \quad (2)$$

By adjusting d, the velocity, v, changes and thus impact force and momentum change. The driving load F_D and distance d can be changed by adjusting the air pressure and the height of sample holder, respectively. In the present experiment, the frequency was controlled at 10 Hz. To determine the impact force, the impact ball was driven under an air pressure to hit on a thin steel button connected to an OMEGA LCKD-500 load cell directly. The button was used to protect the load cell from impacting damage. The impact force F_I and quasi-static pressing force F_P were then obtained and calibrated by a KYOWA PCD-300A data acquisition system. The pressing force F_P depended on the air pressure applied and did not change with varying the distance d under the given air pressure for the air cylinder. After the impact force was obtained, samples were placed at the same distance d and were impacted under the same driving force F_D. Impact tests were carried out at three different distances d. Impact forces at the three distances d under a 400 N driving force were recorded.

2.2. Hard coatings

The samples were coated on 25 mm × 25 mm × 8 mm AISI D2 substrates. The substrates were pre-polished with 600 grit sandpaper, and heat treated to be 58.5–59.2 HRC. The coatings on the AISI D2 samples included two PVD coatings, CrN and TiAlN and one CVD coating, TiC. The coating thickness was determined on cross sections of the coatings using an optical microscope. Nanoindentation (Hysitron Ubi1) was used to measure the elastic modulus and hardness of each coating. The testing load used was a 1 mN with the loading and unloading times of 10 s, respectively. For comparison, a Vickers microhardness tester was also used to obtain the hardness using an indentation load of 25 g. The microhardness of coatings was slightly lower than the nanohardness likely due to the deeper indentation during the Vickers tests and the consequent contribution from the softer substrate. Table 1 gives the thickness and mechanical properties of the coatings.

2.3. Impact procedure

The frequency of impact was set as 10 Hz and the driving force was set as 400 N. By varying the distances d, impact forces were set as 200 N, 400 N and 600 N. 10,000 cycles of impacts were carried out for each coating at the three distances (i.e., the three loads), respectively. The impacts were also performed on the substrate under 7 impact loads ranged from 100 N to 600 N. Prior to the experiment, both the impact ball and samples were cleaned with acetone. A new steel ball was used for each impact test. After impacts, the coatings were cleaned with acetone and the crater sizes were measured using a Buehler Omnimet optical microscope. In addition, a scanning electron microscope (SEM, JEOL JSM-5800LV) with energy dispersive x-ray (EDX) analysis operating at a 15 kV voltage was used to evaluate the failure behaviour in the impacted regions.

3. Results and discussion

Impact forces at the three distances d under a 400 N driving force were recorded and shown in Fig. 2. During the impacts, the driving force applied on the piston in the air cylinder by air pressure accelerated the impact body which generated the impact force when the impact ball punched the tested samples surface. Then, the driving force transformed into a quasi-static build-up force during the late stage of the impact cycle and acted as a pressing force applied on the sample surface after the early impacting. According to Eq. (2), under the constant driving force F_D, the three accelerating distances d would lead to three different velocities and thus produce

Table 1
Thickness and mechanical properties of coatings.

Coatings	Thickness (μm)	Berkovich hardness (GPa)	Vickers hardness (GPa)	Elastic modulus (GPa)
CrN	7.1	18.9	18.2	312.1
TiAlN	2.9	29.7	26.2	315.9
TiC	9.2	29.4	28.4	305.2