

Surface Fatigue Cracking Behavior of a CrN-Coated Tool Steel Influenced by Sliding Cycles and Sliding Energy Density

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ABSTRACT

Light-weighting of vehicles is one of the challenges for transportation industry due to the increasing pressure of demands in better fuel economy and environment protection. Advanced high strength steels (AHSS) are considered as prominent material of choice to realize lightweight auto body and structures at least in near term. Stamping of AHSS with conventional die materials and surface coatings, however, results in frequent die failures and undesired panel surface finish. A chromium nitride (CrN) coating with plasma nitriding case hardened layer on a die material (duplex treatment) is found to offer good wear and galling resistances. The coating failure initiates from fatigue cracking on the coating surface due to cyclic sliding frictions. In this work, cyclic inclined sliding wear test was used to imitate a stamping process for study on development of coating fatigue cracking, including crack length and spacing vs. sliding-cycles and sliding energy densities. The purpose of this study was to examine the effect of testing cycles and sliding energy work on evolution of coating fatigue cracking. In addition, the proportion of total energy transferring to surface energy as a path of energy dissipation through generation of new surfaces of cracks was analyzed. The result indicated that such an energy conversion was insignificant; suggesting that the computing simulation output should also include information of stresses on the die surface and more attention should be paid on response of the coated die material to the stresses.

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1. INTRODUCTION

Light-weighting of vehicles needs to be addressed without compromising from passenger safety and in a cost-effective way. Among the alternatives, advanced high strength steels (AHSS) are considered as prominent material of choice to realize lightweight auto body and structures at least in near term. Stamping of AHSS with conventional die materials and surface coatings, however, results in frequent die failures and undesired surface finish. Several investigations including development of alternative substrate materials and surface coating technologies were reported in the literature to address excessive wear problems [1].

Combating the die wear is one of the crucial challenges in sheet metal forming industry due to increased level of contact stresses at the forming die/sheet blank interface in addition to the elevated springback issues in stamped parts. Wear and springback issues lead to unexpected production interruptions, quality problems, rework and economic losses. These problems are preponderantly experienced when stamping of advanced high steels (AHSS) is considered. The term "galling" is used to describe this excessive from of wear, which is combination of adhesive and abrasive actions. The first one leads to material pick-up (usually from sheet surface) whereas the latter results from cold welded particles [1].

In order to control and/or minimize wear, several countermeasures such as improvement of substrate material (chemical composition, uniform particle distribution, fine particles, hardness, toughness, etc.) and applications of hard-coatings and surface treatments (PVD, CVD, TD, and others) as well as use of proper lubricants (liquid, solid, etc.) have been put into effect [1-2]. Plasma surface technology has become a necessary engineering way for stamping dies to have the improved surface hardness and wear resistance. The surface technology includes plasma nitriding and Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD). The PVD describes a variety of vacuum deposition methods which can be used to produce functional thin films and hard coatings through the heating or sputtering or cathodic-arc to produce a vapor of material, which is then deposited on the object which requires coating. Common industrial coatings applied by PVD are titanium nitride, zirconium nitride, chromium nitride, titanium aluminum nitride [2].

Chromium Nitride (CrN) is used as a coating material for wear and corrosion prevention of mechanical components and in metal forming and plastic moulding applications [2]. A CrN coating deposited by PVD method shows good wear resistance and good seizure resistance. Recently, some researchers have reported the difference between PVD hard coatings and metal substrates using surface free

energy and have pointed out that the polar component of the surface free energy influences the adhesion [3]. In many situations, mechanical components and stamping die materials are often subjected to combined attacks of impact and sliding loads leading then to surface damage. Thus, there is still a need for a testing method that can study wear caused by repetitive impact-sliding motions at high contact stress conditions [4]. It is known that the influence of the sliding cycles and sliding energy accumulation on behavior of the surface fatigue cracking evolution is not well studied yet. There is a need to understand that how the surface cracks generating new surfaces would be functioned as an energy dissipation method through converting the sliding energy to the surface energy.

In this paper, an inclined impact-sliding wear testing method was used to reveal fatigue cracking behavior of a CrN coating on hardened S0050A steel. It provides a case for us to observe the formation of cracks on the coating, the evolution of surface fatigue failures under the repetitive impact-sliding forces and the percentage of sliding energy transferring to surface energy.

2. EXPERIMENTAL DETAILS

2.1. CrN Coating on Cast Steel

In this paper, a CrN coated S0050A steel was used as a coupon for inclined sliding wear test. The sample size was 25mmx25mmx6mm. The S0050A cast steel substrate material was annealed by heating to 872-925 °C and holding for a minimum of one hour plus one hour per 25 mm of section thickness using maximum section thickness. The sample was furnace cooled to 560 °C at a rate not to exceed 45 °C per hour, then air cooled at room temperature. The chemical composition of S0050A materials is 0.4%-0.5% C, 0.2%-0.5% Si, 0.9%-1.2% Mn, 0.8%-1.1% Cr, 0.35%-0.50% Mo, 0.15% V, 0.05% S, 0.045% P and Fe balance (all in weight percent, respectively) [5]. The steel substrate was followed with a plasma nitriding treatment. A CrN coating was then deposited on the nitrided substrate using a cathodic arc evaporation technology. A typical process temperature for the vacuum PVD (physical vapor deposition) coating was around 350 °C. The coating thickness was ~5 µm, and hardness ~2200HV.

2.2. Impact-sliding Wear Test Method

The schematic of a repeated inclined impact-sliding tester is shown in Figure 1, where an illustration of a typical impact-sliding scar is included. To start an impact-sliding test, the flat specimen is secured on the sample holder. The sample holder functions as a rocker which can rotate around a fixed roller bearing due to the pressing of the indenter ball when the piston moves up and down. Driven by the piston, the indenter ball first impacts (with a load of F_i) and then pushes downward against the flat coating specimen, causing sliding between the ball and the flat specimen in the first half of each test cycles. After a short pause at the end of sliding scar the tip of the tail part (where it has the maximum pressing force of F_{pmax}), the ball slides reversely on the surface of the flat specimen and is then disengaged from the surface in the second half of the test cycle. The sample holder has an angle of 20° to the horizontal direction in the

static state. A hard spring (Figure 1 (6)), which acts as a driving device for the rocker to return back, is fixed on the other end of rocker arm. During the impact test it can rotate the rocker back to its initial position when the ball moves upward (Figure 1). A 10mm diameter bearing steel ball was used as the impact ball that can move in reciprocate mode in the vertical direction driven by a piston in the compressed air cylinder [4].

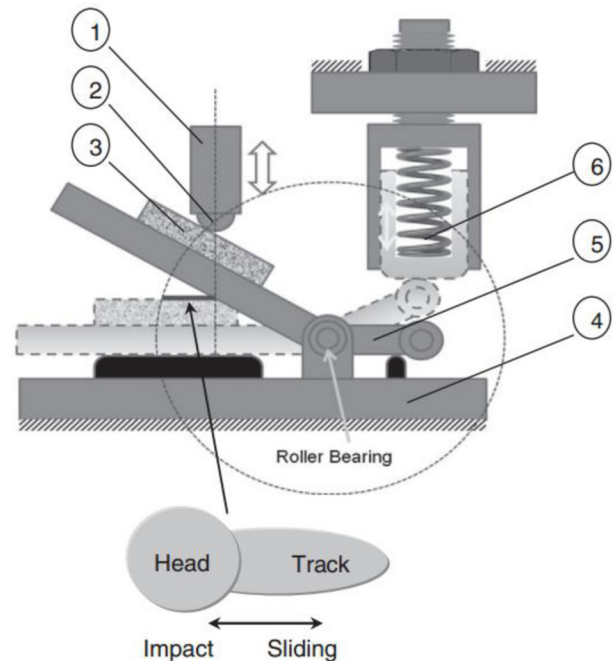


Figure 1. Schematic of impact-sliding wear tester. 1-ball indenter drive (e.g., air cylinder), 2-ball counterpart, 3-flat specimen (i.e., coating), 4-rigid frame, 5-rotatable rocker, 6-return drive (e.g., spring) [4].

The test allows the simulation of the combination of impact surface fatigue failure and sliding wear failure under repetitive high local loads, as encountered by machine parts subjected to impact or tools used in interrupted cutting or cold forming. The impact force and frequency are variable to adjust the test conditions for different applications, by varying the dynamic force and the impact speed of the ball. Each cycle of impact-sliding force can be measured during the test. A load cell with a PCD30A signal collector has a high sampling frequency of 10,000 Hz. The impact frequency is 5 Hz in this study, which means the whole impact period, with the up and down motion, is 200ms. The ball was changed and the coating surface cleaned with acetone before starting each tests with a fresh area in dry wear condition [4].

2.3. Test Conditions

According to the Section 2.2 mentioned above, the loading geometry is a sphere-plane system and the stress distribution that arises from this contact is typically Hertzian [4]. Based on some previous tests, 24psi air pressure in our system provides a $F_i/F_p = 140N/300N$. The load curve depicts that there are three stages in each impact cycle, i.e. impact loading stage, increased loading stage and the maximum load stage. When the counterpart ball contacts the impacted sample surface

for the first time, the first peak of the load arises, which is defined as an effective impact load- F_i . Under the loading condition of this case, the S0050A substrate was yielded, and the coating was locally deformed with fatigue cracks after a certain cycles of impact. After the counterpart ball completed the first full contact with the coating surface and form a deep impact crater, almost no rebounding occurred since there was a compression that was pre-set on the spring of the spring-driven device. After the air cylinder kept pushing, the load continued to rise until the maximum pre-setup pressing load (F_p). This is named as the pressing load stage, in which a long tail with sliding failures can be formed after a certain cycles of the test. In order to study the evolution of the coating failures, three different impact cycles (i.e., 500, 1000 and 1500 cycles) were applied.

2.4. Statistics of Crack Evolution

The distributions and evolutions of surface fatigue failures in different areas of the impact-affected zone were observed by means of optics microscopy (OM) and scanning electron microscopy (SEM). OM images were taken at magnifications of 50 times and 200 times, separately, and scale bars were added on the images. Since the fatigue cracks in all cases cannot be displayed in one image under the 200 times scope, a number of images was taken at different locations of the same wear track. Photoshop was used to combine those scattered images into a complete one. The stitched OM image of a wear track was then input into AutoCAD which was used to sketch the fatigue cracks by tracing over the shapes of the cracks. The drafted curves were floating on top of fatigue cracks. The number of the fatigue cracks and the lengths of each crack were calculated by the query function in the AutoCAD. To reduce the work loads and avoid possible uncertainty from the effect of initial pulsed-like impact loading portion, only cracks on the second half of the wear track (from middle to tail) were recorded in each of the OM images. These data were recorded and put into Excel. Excel function was used to plot the relationship of fatigue cracking evolution vs. the testing cycles. The statistical error could be about 5%.

3. RESULTS AND ANALYSIS

3.1. Fatigue Cracking vs. Test Cycles

For the given impact force, the durability of coating is characterized by the number of impact-sliding to failure, this being when the substrate materials appear. After impact-sliding tests with 500, 1000 and 15000 cycles, the surface fatigue cracks were examined in details based on OM observations. Figure 2 shows the distribution of fatigue cracks on the whole impact-sliding scar after 500, 1000 and 1500 cycles' tests, respectively. To avoid possible discrepancy from the effect of impact portion, this study was focusing on the sliding portion starting from the middle wear track to the tail end. After a number of OM micrographs (x200 magnification) of the wear track were taken and stitched together, the stitched image was input to AutoCAD which was then employed to sketch the cracks on the half of the wear scar (from middle to tail parts). The drafted curves floating on top of fatigue cracks are given in Figure 3.

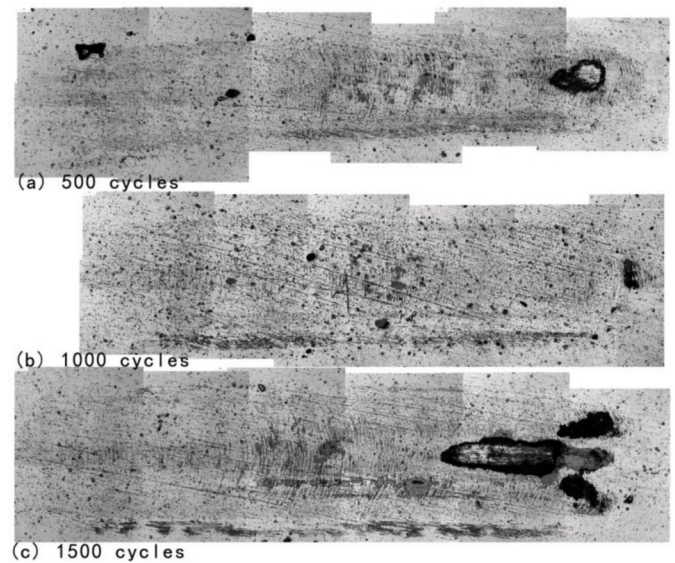


Figure 2. OM micrograph of impact-sliding scars on the coating after 500, 1000 and 1500 cycle tests.

Figure 4 shows the wear tracks (from middle to tail) under different test cycles. A series of circular cracks were formed on the coating surface after the 500 cycles' test (Figure 3 (a)). Material transferring was observed on the areas where the fatigue cracks appeared and the coating surface roughness increased as a result. Chipping and peeling of the coating materials occurred in the center of contact area. With the increasing of the test cycles to 1000, a greater number of cracks were observed there (Figure 3 (b)). After 1500 cycles' test, chipping and peeling of the coating materials were expanded to the rim areas (Figure 3 (c)).

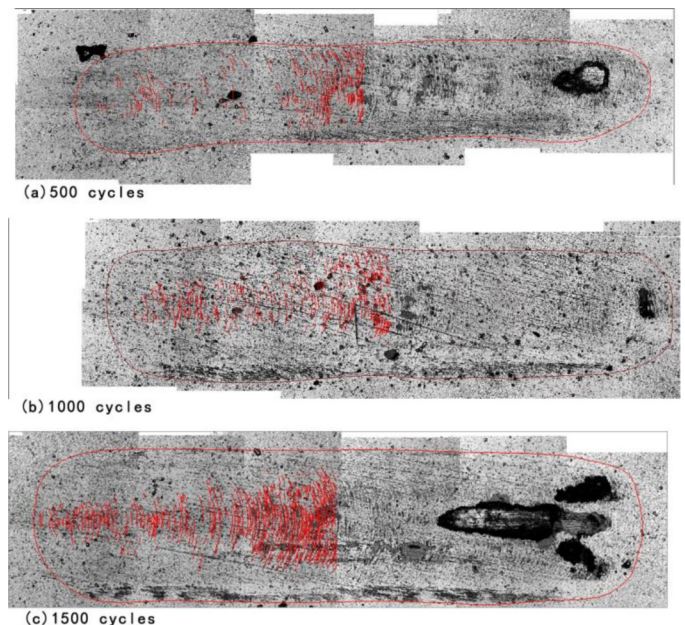


Figure 3. Drafted curves floating on the top of fatigue cracks of OM micrograph of impact-sliding scars on the coating after 500, 1000 and 1500 cycle tests.