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Indentation Parameter Combinations on the Failure in a Coated System

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Abstract

The deposition of wear resistant thin films represents an usual procedure to improve the tribological behavior of mechanical components and parts. Depending on the application, the fracture toughness of the film plays a key role and different methods were developed to evaluate this mechanical property. Recently, the film fracture toughness was related to the distance between circular cracks generated during the spherical indentation of coated systems with soft substrates. In this work, analyses were conducted to further understand the phenomenon of circular crack formation during indentation, including the effect of load and indenter diameter.

Films of chromium nitride (CrN) were deposited onto AA 6061 aluminum substrates through a commercial physical vapor deposition (PVD) process. Coated specimens were later indented by spheres with diameters from 1.59 to 6.35 mm, which applied normal loads from approximately 196.1 to 490.3 N. Similar amounts of circular cracks were obtained when an increase in indenter diameter was associated with an increase in normal load.

Keywords: Circular cracks, Coated system, Indentation parameters, Pile-up

I. INTRODUCTION

The deposition of wear resistant thin films on different substrate materials is a common practice to improve the tribological (wear and friction) behavior of different components and parts. For this reason, it is necessary and important to evaluate the coated systems mechanically. A simple method for the characterization of these systems is the indentation test [1-5], where indenters with different geometries are used, such as spheres, cones or pyramids [6]. In coated systems, the selection of spherical indenters is frequently preferred over those with pyramidal geometry since the former is associated with a reduction of the stresses in the film [5]. However, the maximum principal stress increases as the diameter of the indenter increases, indicating that the use of larger indenters may not be an effective option to avoid crack development during the indentation process [2].

The indentation test is also used to understand the mechanisms governing failure in coated systems [7]. This type of study analyzes the development of contact stresses during the process, under which the coated systems can fail due to a loss of film/substrate adhesion [8], a failure designated as adhesive, or due to the fracture of the film, a failure designated as cohesive.

In terms of the film fracture toughness, some indentation techniques are based on the propagation of cracks from the corners of pyramidal indentation marks. However, depending on the film properties, cracks are not always observed at the low loads necessary to prevent an influence from the substrate [8]. The fracture toughness has also been evaluated through microindentation methods [6,9], but the loads applied in such cases usually result in penetration depths that are larger than the film thickness, such that the result may be a measurement related to the toughness of the coating-substrate system Alternatively, an instrumented indentation method was proposed, which is based on steps observed on the curves of depth of penetration as a function of applied load [10-12]. However, the steps in those curves are not always observed during low load indentations conducted on thin film systems.

As consequence of the indentation, arrangements of circular cohesive cracks may be observed near the perimeter of the impression [2,5,6,8]. According to Thomsen et al [2], this type of cracks is caused by tensile radial stresses present near the indentation edge. In some cases, radial cracks occur both inside and outside the indentation zone and usually, circular cracks are the preferred cohesive fracture pattern in systems with hard thin films deposited onto a ductile substrate [5,13].

In many cases, the propagation of circular cracks was associated with the amount of substrate indentation pile-up, which represents the material that moves upward at the indentation corner [2,3,11]. Experimental works have also been conducted to study the circular cracks at the contact edge of an indentation, however, apparently only little attention was placed on the circular cracks, which may carry important information regarding the characteristics of the film. In recent works [14-17], it was demonstrated that the number and location of circular cracks may be related to several factors, which include the geometry, the friction coefficient between the film and indenter, the substrate-film mismatch in elastic modulus, the roughness of materials, the level of film residual stresses and the film fracture toughness.

In this work, a series of indentations was conducted using indenters with spherical geometry, which applied normal loads on a system with soft substrate coated with a wear resistant thin film.

2. EXPERIMENTAL PROCEDURE

2.1 Coated system

The specimen substrate was a piece of AA 6061 aluminum with dimensions of 16.6 x 12 x 3 mm^3 (Schematic on Fig. 1), which was polished until mirror finish. A film of chromium nitride (CrN) with thickness of approximately 4 μm was deposited onto the aluminum substrate following a commercial physical vapor deposition (PVD) process at low temperature. Fig. 1b, presents the characteristics of the film surface, when observed in an optical microscope.

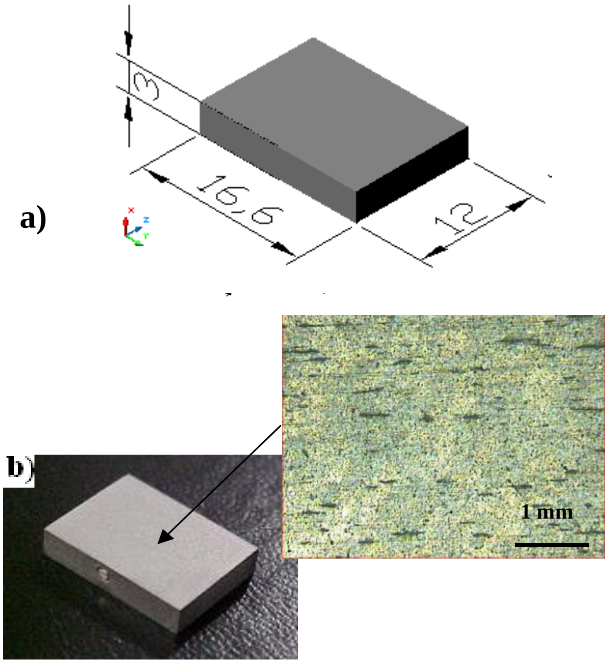

Figure 1. Coated system CrN-Aluminum. a) Specimen dimensions in milimeters b) Superficial aspect of the CrN coating obtained through a commercial PVD process

2.2 Indentation Loads and indenter diameters

The loads used in the indentation test were 9.8, 49, 98, 196.1, 294.2, 490.3 N. Spheres with diameters of 6.3, 3.2, 1.59 mm (1/4, 1/8 and 1/16 inch) were used in the indentations, which are diameters of spheres used in different Rockwell hardness tests. Indentations were conducted in a BUEHLER VMT-7 hardness tester equipment.

After testing, the indentation marks were analyzed through optical and scanning electron microscopy (SEM). The amount of pile-up in each indentation was evaluated with a roughness equipment SURFCODER IF 1700α. This equipment was set at a roughness measurement configuration, wich allows the measurement of indentation pile-up, but does not allow the measurement of the indentation depth

3. RESULTS AND DISCUSSION

The optical microscopy analysis indicated that, independently of the diameter of the sphere, no circular cracks were observed with loads of 98 N and lower.

The fig. 2, presents the indentation marks obtained with different indenter diameter and with the loads that resulted in circular crack formation. In each of these cases, the number of circular cracks was roughly measured, indicating that a similar amount (from 10 to 15) of cracks was generated for the conditions on the principal diagonal of Table 1.

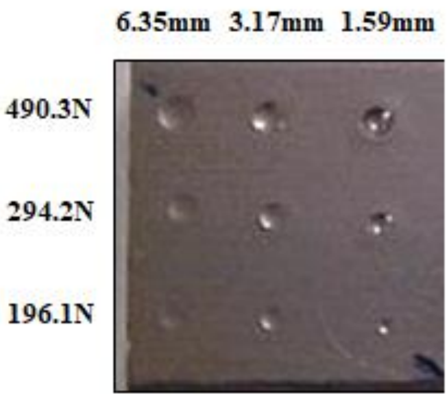

Figure 2. Indentation marks generated in the coated system during indentation.

Table 1. Number of cracks obtained as a function of the load and indenter diameter

Normal Load (N)	Indenter Diameter		
	6.35 mm	3.17 mm	1.59 mm
490.3	10 - 15	>30	>30
294.2	≤5	10 - 15	>30
196.1	≤5	≤5	10 - 15

Fig. 3, shows the number of cracks obtained for the load-diameter combinations on the principal diagonal according to Fig. 2, as well as, with the table 1.

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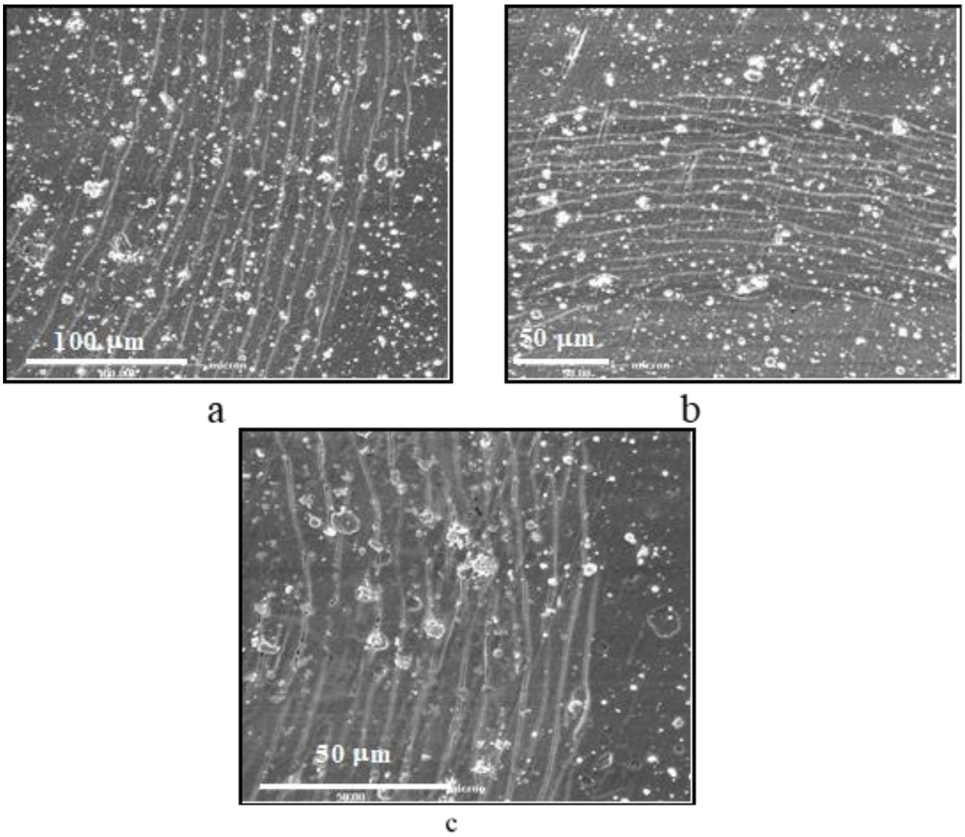

Figure 3. Cracks observed inside the indentation mark. a) Indentation with indenter of 6.35 mm and 490.3 N b) Indentation with indenter of 3.17 mm and 294.2 N c) Indentation with indenter of 1.59 mm and 196.1 N.

The Fig. 4, shows circular cracks obtained inside the contact region for load-indenter combinations below the principal diagonal. only few circular cracks (approximately 5 or less) were observed (Fig. 4a). More than 30 circular cracks were observed at the conditions above the principal diagonal (Fig. 4b). The Fig. 5, shows the heights of the pile-ups obtained with different load-diameter combinations.

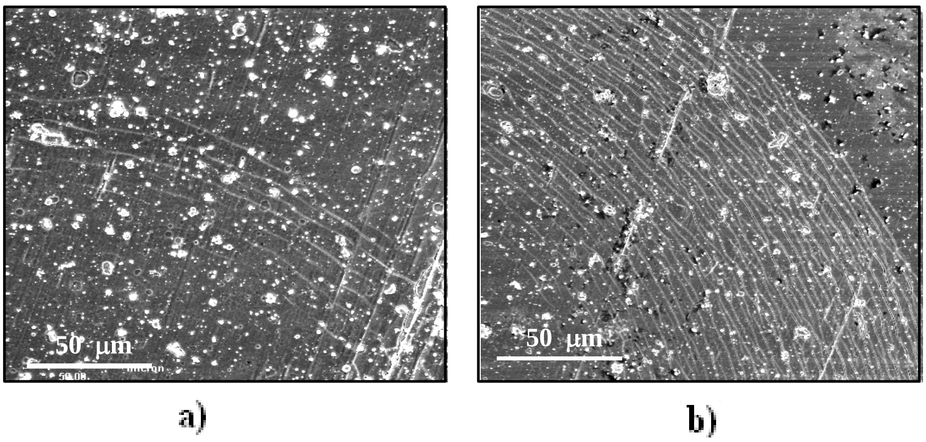

Figure 4. Number of cracks observed by scanning electronic microscopy (SEM) in the inside to the contact area of indentation. a) Indentation doing with indenter of 3.17 mm and load of 196.1N b) Indentation doing with indenter of 3.17 mm and load of 490.3 N.

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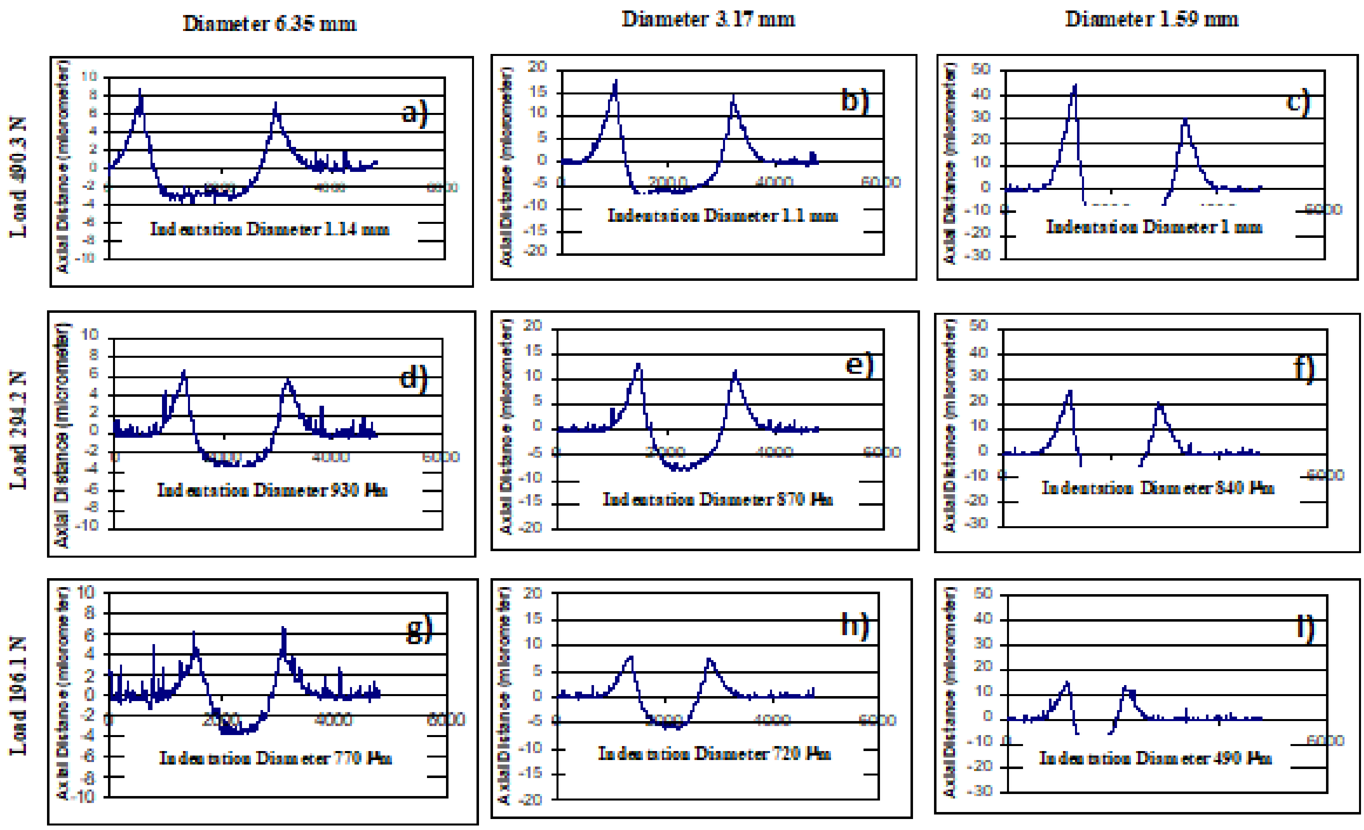

Figure 5. Quantification of pile-up generated in each one of the indenter-load combinations. a) Diameter of 6.35 mm and load of 490.3N, b) Diameter of 3.17 mm and load of 490.3N, c) Diameter of 1.59 mm and load of 490.3N, d) Diameter of 6.35 mm and load of 294.2N, e) Diameter of 3.17 mm and load of 294.2N, f) Diameter of 1.59 mm and load of 294.2N, g) Diameter of 6.35 mm and load of 196.1N, h) Diameter of 3.17 mm and load of 196.1N, i) Diameter of 1.59 mm and load of 196.1N

As expected, with the same indenter, an increase in normal load resulted in an increase in the height of pile-up. The figure also indicates that pile-up heights were similar for the conditions on the principal diagonal (Figs 5a,e,f). Higher pile-ups were measured above this principal diagonal (fig. 5c) and lower pile-ups were found in the conditions below this diagonal (Fig. 5g).

According with the results, the film circular cracks observed on the edge of an indentation are associated with the bending of the film. Following an analogy with a bar that is bended, higher tensile stresses should be expected either when the amount of bending is increased or when the bending curvature is decreased. During an indentation, the amount of bending is mainly controlled by the height of indentation pile-up, and curvature is also affected by indenter diameter. An analysis of the conditions along the principal diagonal (Table 1) which had a similar behavior in terms of the amount of circular cracks, indicates that the pile-up height was similar in the three load-diameter combinations (condition obtained in Fig. 5). This fact suggests that, when compared to normal load and indenter diameter, pile-up height is the predominant factor in determining the tensile radial stresses and, consequently, the amount of indentation circular cracks.

In addition, from the results obtained, it is possible to identify that for the coated system studied, it is possible to obtain the same result (circular cracks) by identifying the most suitable combination of load level and indenter diameter. This is how using a low load with a small indenter can generate the same consequences as using a high load with a larger indenter. In other words, the plastic deformation capacity of the system depends on the deformation of the substrate and in turn on the adequate selection of the load and indenter parameters used for the evaluation of the coated system.

4. CONCLUSION

This work confirmed that the indentation of coated systems with substrates presenting an elastic-plastic behavior can result in series of circular cracks inside the contact region of the indentation. The number of circular cracks was related to different factors, such as the diameter of the indenter and the applied normal load.

For the load-diameter combinations studied in this work, the height of the indentation pile-up (ability of plastic deformation) was the most important factor that determined the amount of circular cracks that propagated in each case.

The identification of the normal load and size indenter combination allows to analyze the deformation capacity of the coated systems and to evaluate the cracking capacity of the coating.

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