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Mechanical damage of hard chromium coatings on 416 stainless steel

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ABSTRACT

Hard chromium coatings are widely used for high performance components due to their superior wear and corrosion resistance. In this study, 416 stainless steel bars were chromium electroplated commercially with different thickness. Mechanical properties and residual stress were measured using a nano-indentation system and X-ray diffraction, respectively. Image analysis technique was used to measure inherent crack density. Residual stress in the coating increases with increasing thickness leading to an increase in inherent crack density. An indentation study was carried out to investigate the mechanical damage of hard chromium coating as a function of thickness. Different failure modes were observed when hard chromium coatings were indented with a spherical indenter including Hertzian cone cracks, radial cracks, bend cracks, lateral cracks and coating delamination. Three thickness regions of distinctive cracking modes were identified. Thin coating region exhibited through-thickness Hertzian cracks. Hertzian and coating-bend rings, cone, surface radial cracks and coating bottom surface radial cracks were observed in intermediate coating region. This region exhibited highest cracking damage density. In thick coatings Hertzian cracks were observed. It was found that two factors affect the cracking damage: residual stress that increases with increasing thickness and bending stresses that decrease with increasing thickness. The resultant effect was maximized at intermediate coating thickness.

1. Introduction

Hard chromium plating has a wide range of applications in the aerospace and automotive industries. Parts are chromium electroplated when some of the following characteristics are required: low coefficient of friction, high melting point, high hardness, and a resistance to wear and corrosion. Chromium electrodeposition is also used to salvage or refurbish worn components. Since hard chromium parts are often used in critical situations, understanding the failure mechanism of hard chromium coatings due to mechanical damage is important. Unfortunately, a comprehensive study on indentation damage of hard chromium coating is lacking in the open literature. The main objective of this study is to investigate the mechanical damage of hard chromium coatings as well as to study the effect of thickness, residual stresses and applied indentation load on hard chromium coatings behavior. In addition, crack types and formation mechanism are investigated.

Several bath chemistries can be utilized in the process of chromium electroplating. Plating speed and deposit characteristics depend on the particular bath chemistry employed. Process parameters (i.e., current density and bath temperature) involved in electroplating must be well controlled to produce the desired deposit [1–3]. Chromium is deposited in the form of a pure metal or a metal hydride, depending on solution composition and other operating conditions. The metallic form has a body-

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centered cubic (BCC) crystal structure, while the metal hydride takes the structure of either hexagonal or face-centered cubic. Hydrides are not stable and decompose to produce BCC chromium metal and hydrogen. The decomposition results in shrinkage in volume that induces tensile stress causing the coating to crack [4]. Guffie [5] suggested that internal residual stress increases with coating thickness. When residual stresses exceed the chromium's tensile strength cracking occurs and stress is released. As electrodeposition proceeds, another layer of chromium heals over the existing cracks and stresses start to accumulate again until another set of cracks forms. This cyclic process continues during electroplating. Consequently, healed-over cracks and open cracks are observed on chromium coating surfaces. Dennis et al. [6] explained the cracking mechanism using an instantaneous stress/thickness curve along with images of cracking patterns at different coating thicknesses, where stress increases with thickness and when it cracks, a sharp decrease in stress is observed. Inherent crack density increases with increasing thickness. These cracks do not extend to the base metal. They concluded that inherent cracks are usually preferred in applications, such as hydraulics as they can hold lubricants. However, they can be potential sites for crack propagation. Inherent cracks and residual stress may play a role in mechanical failure, such as impact and denting during service of hard chromium coating.

A variety of cracks may form by indentation contact on brittle materials. Five main types of cracks due to indentation of brittle monolithic materials were identified in the literature [7]. Cone cracks are generated during elastic loading when a blunt indenter is employed. A cone crack is first generated at the surface as a ring at the periphery contact and then it propagates downward and outward at a characteristic angle with the symmetry axis forming a cone-shaped crack. Radial cracks are generated when a sharp indenter or high loading of a blunt indenter is applied. They form during elastic-plastic loading that leaves plastic impression in the surface. In such circumstance, radial cracks might propagate parallel to the loading axis, generally starting at the edge of the impression (commonly at the impression corner). Another type of crack is median cracks that may be formed parallel to the loading axis during elastic-plastic contact, below the quasi plastic zone, bounded by plastic zone or the surface. Lateral cracks can form underneath the plastic deformation zone, parallel to the material surface. Lastly, half-penny cracks are a mixture of median and radial cracks and can develop during unloading. This type of crack begins either with radial cracks propagating downward or median cracks extending upward. The type of cracking present depends on several factors including material, indenter, maximum applied load, and environment. Generally, one cracking system or more may be present in a single indentation event [7]. Chen [8] reported that these types of cracks were identified on brittle thick coatings as well. Cracks form perpendicular to stress that exceeds material strength and initiate where the maximum stress is located.

Understanding the stress distribution in the contact zone can help predict crack types (damage mode). Often a Hertzian-type contact test (spherical indenter) is used to evaluate damage mode during contact of monolithic materials and coatings. Fig. 1(a) and (b) show Hertzian stress trajectories and contours for the principal normal stresses, respectively. The former is used to display principal stress direction, while the latter is to display the principal stress distribution. The upper side of Fig. 1(a) is top view of the indention where the black region is the contact area of diameter a-a, whereas the lower part is cross-sectional view of the indention. Principal stresses are defined as $\sigma_{11} \geq \sigma_{22} \geq \sigma_{33}$, respectively. The applied load has a hemisphere distribution within the contact area. Principal stress σ_{11} and σ_{33} are axially symmetric in plane with the loading axis. The circular hoop stress (σ_{22}) trajectories are perpendicular to those of σ_{11} in any plane through the axis of symmetry. The principal stress σ_{33} trajectories have a nearly hyperbola shape that meets the surface perpendicularly. Fig. 1 (b) shows stress

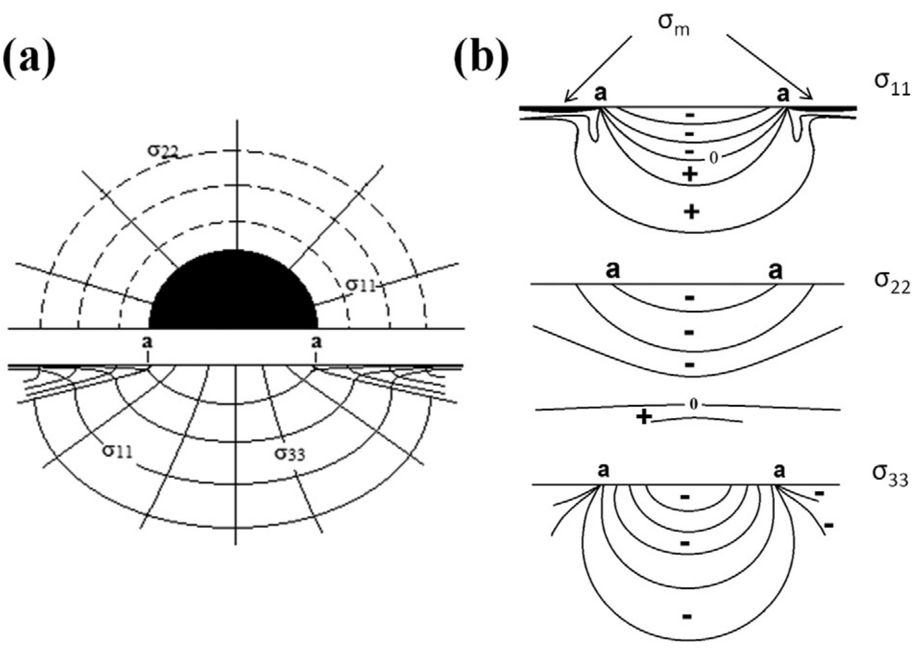

Fig. 1. a) Schematic diagram of principal stress trajectories of near-contact field, surface view (top) and side view (bottom), b) principal stress contours.