Introduction to Ion Beam-Based Coating Technology

by
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The application of performance coatings to precision machined components and manufacturing tooling is done routinely using a variety of coating processes. Electroplating, chemical conversion coating, thermal spray, and physical vapor deposition (PVD) processes are all used successfully for various applications. All of the conventional coating processes have certain limitations in terms of the application temperatures required, the types of base materials that can be coated, and the need for post coating re-finishing. A new process is now being commercialized that has a number of attractive features for the coating of precision components and tools. BeamAlloy Technologies' patented Ion Beam Enhanced Deposition (IBED) process is the most advanced surface treatment process in the industrial marketplace, and offers many advantages when used to coat the surfaces of precision components and tooling to improve resistance to wear, corrosion, and other surface-related phenomena. The nature of the process allows deposition of coatings having a wide range of metallurgical compositions, and with a high degree of control over coating nanostructure. Since it is a physical, not a chemical or thermal process, coating adhesion and growth is achieved without the external application of heat, and processing temperatures can be held below 200 °F (93 °C) if desired. It also provides flexibility in the range of substrate materials that can be coated, and does not require post-coating refinishing. The features of the IBED process are compared to those of conventional coating technologies, and the properties of the wear-resistant coatings deposited by plating, PVD, and IBED are described.

The Universe of Surface Treatments

The range of processes used to treat the surfaces of engineered materials is presented in Figure 1. If the universe of surface treatments is categorized according to two criteria - the first, that the metallurgy produced by the process is equivalent, and the second, that the equipment used to implement the process is related, then all surface treatments can be classified into one of six categories. Heat treatment affects the entire volume of the substrate material and extends to the surface region. It can be done either in air or in a vacuum chamber. Case hardening processes produce a hardened case layer in the surface of a substrate by thermally-driven diffusions of species such as C, N, or B. The case hardening process can be implemented in a salt bath at atmospheric pressure, an elevated pressure chamber (gas nitriding, carburizing) or a vacuum chamber (ion nitriding, carburizing). Plating, conversion coating, and anodizing processes are used to deposit coatings on the substrate surface. They are all chemical processes implemented in an aqueous media contained in a tank at atmospheric pressure. A wide variety of metallic, and metallic oxide coatings can be deposited. Plasma spraying is used to build thick coatings on the substrate surface and there is always a distinct interface between the coating and substrate. Plasma spraying can be done in air at atmospheric pressure or in a low-pressure chamber, and is usually used to deposit metallic or oxide coatings. Physical vapor deposition is used to deposit thin hardcoatings on the substrate surface. A limited variety of metallic nitride, carbide, and oxide, and diamond-like carbon coatings can be deposited. A vacuum environment is required.

Unlike all conventional treatments, IBED is a physical as opposed to a chemical or thermal process. The temperature rise during processing can be held below 200 °F so no thermally-induced volumetric changes in bulk properties or physical dimensions are produced. IBED processing combines the benefits of thermal diffusion processing and conventional coating technologies because the coating atoms first penetrate into the substrate to form a case layer in the surface, and then are grown out from this case layer as a thick coating. Driven in kinetically instead of thermally, IBED coatings are "ballistically bonded" to the substrate thus forming a metallurgical bond that is much stronger than a mechanical or Van der Waals bond. And since the IBED process is kinetically driven, solid solubility limits can be exceeded which is the mechanism that allows deposition of a variety of types of coatings on virtually any substrate material.

Ion Beam Enhanced Deposition

IBED is a physical, non-equilibrium coating process implemented by the simultaneous bombardment of a growing film with an independently controllable beam of energetic atomic particles (see Figure 2). The growing film is generated either by vacuum evaporation or ion beam sputtering. The independent beam of particles consists primarily of charged atoms (ions) extracted at high energy from a broad beam ion source. Beams of either inert species (Ne^+, Ar^+, or Kr^+) or reactive species (N^+ or O^+) can be utilized. Because control of the ion beam is independent of the coating vapor flux, the energy of the ions in the beam can be varied over a wide range and chosen within a very narrow window. This allows a high degree of control over coating nanostructure and optimization of coating properties such as interfacial adhesion, density, grain size/morphology, and internal stresses. Essentially a line of sight process, sources of the reactant fluxes are located so that they simultaneously illuminate the components to be coated (see Figure 3). The components are mounted to an angling, rotating platen assembly that is used to uniformly expose all surfaces of the components to both reactant fluxes.

IBED Process Features

The attractive features of the IBED process are summarized as follows.

LOW TEMPERATURE PROCESSING	Component temperature held below 200 °F No distortion of dimensions or bulk properties
HIGHLY CONTROLLED PROPERTIES	Composition, residual stress, density Uniform nanocrystalline structure
HIGHLY REPEATABLE PROPERTIES	Metallurgical and mechanical Thickness and dimensional uniformity
REPLICATES ORIGINAL FINISH	No change in RMS finish, No need for post-coating re-polishing
VARIETY OF COATINGS	Metals, nitrides, oxides, and carbides, all deposited with the same processing system
SUBSTRATE INDEPENDENT	Metals, plastics, ceramics, and glass can be coated
NO EPA/OSHA IMPACT	No toxic feedstocks used No toxic waste generated

Coatings Available and Coating Properties

The types of coatings that have been deposited by the IBED process include metals (Cr, Ni, Ti, Al, Cu, Ag, Pt, Au), metallic nitrides (TiN, Cr_2N, Si_3N_4, AlN, ZrN), oxides (SiO_2, Al_2O_3), and carbides (DLC). Coating thicknesses in the range of 1 to 10 microns (40 to 400 µ-in.) (1 µmeter = 10^{-6} meter and 1 micron = 1 µmeter) are technically and economically feasible. Since coating nanostructure is highly uniform, the mechanical properties of IBED-deposited coatings are better than the equivalent coatings deposited by plating or PVD. The IBED coatings exhibit improved adhesion and cohesion, are significantly smoother both macroscopically and microscopically, and are free of voids and pinholes. And the coating properties are highly repeatable – a must for high volume production.

Wear-Resistant Coating Performance Comparison

A study was done to compare the performance of a series of wear-resistant coatings deposited by plating, PVD, and IBED processes. The coatings included plated industrial hard chrome, PVD-deposited titanium nitride (TiN) and diamond-like carbon (DLC), and IBED-deposited TiN. Properties measured included coating adhesion, durability, and abrasive wear rate.

Adhesion/Durability

A qualitative measurement of hardcoating durability and adhesion can be made using a Rockwell "C" indent test (VDI Guideline 3198 procedure). Coatings are deposited on a polished, hardened steel coupon (R_C >60) to a thickness of between 1 and 3 microns. A standard Rockwell diamond indenter is used to indent the surface for a "C" scale measurement (150 Kg). The indented area is examined at a magnification of 200X and the cracking pattern is observed. Hardcoatings with good cohesion show little or no fracture lines extending radially from the center of the indent outward towards and beyond the perimeter of the circular indent. Also, no cracked islands appear in the indent crater or along the crater perimeter. Hardcoatings with good adhesion show no delamination of the coating either in the crater or adjacent to the coating perimeter.

The results of the VDI-3198 test for all four coatings tested are presented in Figure 4. Figure 4A shows the performance of the hard chrome plating. There are radial fracture lines indicating cohesive failure of the chrome plating on the conical indent surface. Most of the radial fracture lines in the coating extend beyond the indent perimeter. A number of cracked islands have formed but there is no delamination of the coating either in the indent or adjacent to it indicating good adhesion under conditions of high stress. Figure 4B shows the performance of the PVD-deposited DLC. There are many radial fracture lines and cracked islands within the conical indent zone indicating poor cohesion. Many of the cracked islands have delaminated from the surface, and there is complete delamination of the DLC coating beyond the conical indent indicating poor adhesion under conditions of high stress. Figure 4C shows the performance of the PVD-deposited TiN. The high density of radial fracture lines within the conical indent and beyond the indent perimeter indicate poor coating cohesion and high coating friability. The presence of cracked coating islands in the conical indent and at the indent perimeter margin, many of which have delaminated, indicates marginal adhesion to the hardened steel substrate under conditions of high stress. Figure 4D shows the performance of the IBED-deposited TiN. There are minimal radial fracture lines with tearing of the coating on the conical indent surface indicating excellent cohesion within the coating. Some radial fracture lines with very slight tearing of the coating are seen beyond the indent perimeter. The darkened areas on the conical indent are dirt particles transferred from the diamond indenter to the indented surface. The absence of multiple cracked coating islands indicates excellent adhesion to the hardened steel substrate under conditions of high stress.

Abrasive Wear-Resistance (Rate)

The abrasive wear-resistant performance of coatings can be tested using a Taber Abraser. Performed according to a standard procedure, SAE/AMS-2438A (SAE International), coatings are deposited on 3.75 inch (9.5 cm) diameter disks that are rotated against resilient rollers volumetrically impregnated with 50-micron diameter alpha-phase aluminum oxide grits. The coated disks are weighed, run for a fixed number of cycles, and then re-weighed. The thickness of coating material worn away can then be calculated. Since standard test parameters are used (grit sizes, wheel RPM, and surface loading), the wear rates obtained are directly comparable as measures of abrasive wear resistance.

All four coatings studied were deposited on 3.75 inch (9.5 cm) diameter, hardened (R_C 64-66) high speed steel disks that were lapped to a highly polished finish of 0.025 µmeter Ra (1 µinch AA). The coatings were deposited to equivalent thicknesses, approximately 4 microns. The results of the abrasive wear test for all four coatings are plotted in Figure 5 and compared to the wear rate of S7 tool steel hardened to Rockwell “C” 60. The wear rate measured for hardened tool steel (S7) was 1.3 microns per 10,000 revolutions. Industrial hard chrome plating, usually applied as a combination corrosion- and wear-resistant coating, showed a wear rate of 0.6 microns per 10,000 revolutions, a factor of 2X reduction in wear-rate compared to hardened S7 tool steel. The PVD-deposited DLC coating showed a wear rate of 0.04 microns per 10,000 revolutions, a reduction in wear rate of 32X compared to hardened S7 steel and a 15X reduction compared to hard chrome plating. Both the PVD- and IBED-deposited TiN showed equivalent wear rates of 0.015 microns per 10,000 revolutions, reductions in wear rate of 86X, 40X, and 3X compared S7 steel, hard chrome plating and PVD-deposited DLC respectively.

The IBED process has many features that make it attractive for use on precision parts and manufacturing tooling. Flexibility in the types of coatings that can be applied to a wide variety of substrate materials, plus the low deposition temperature makes the use of these IBED deposited coatings feasible for a wider range of industrial applications than conventional coating processes. And, IBED-deposited coatings, due to the nature of the process, have improved mechanical properties such as adhesion and cohesion, important when used under conditions of high stress. The combination of attractive IBED process features and improved IBED-deposited coating properties make IBED the technology of choice when high performance coatings are required.

Figure 1: Universe of surface treatment technologies catagorized according to the major technologies applied.

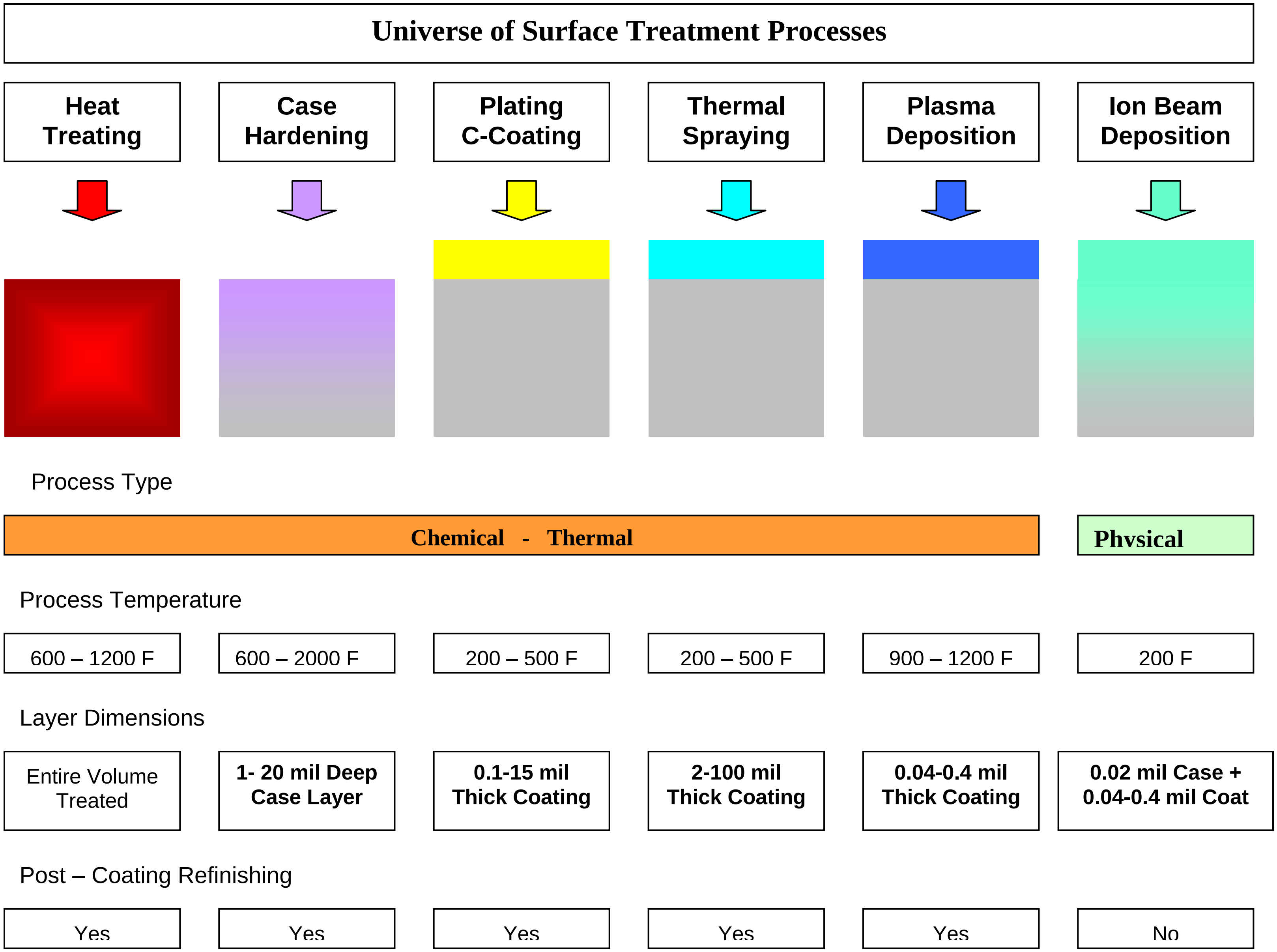


Figure 2: IBED process

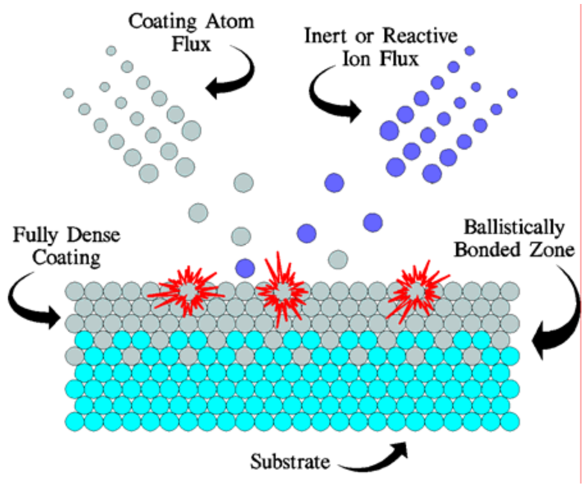


Figure 3: IBED process geometry

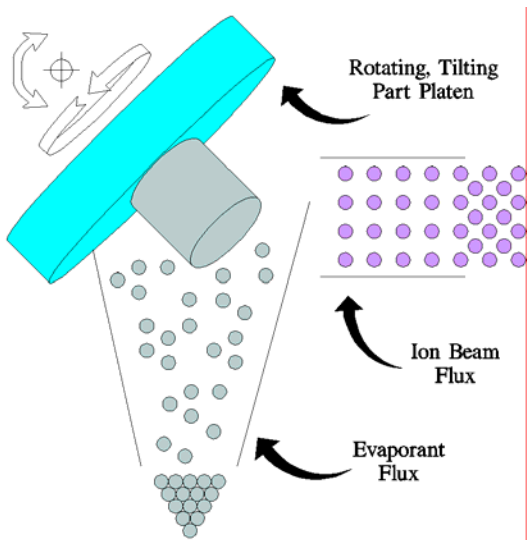
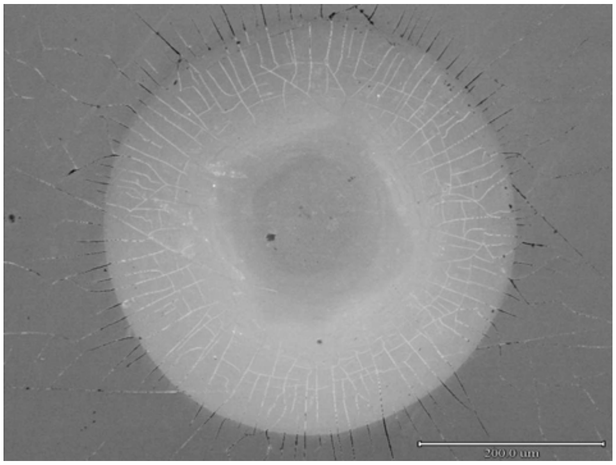
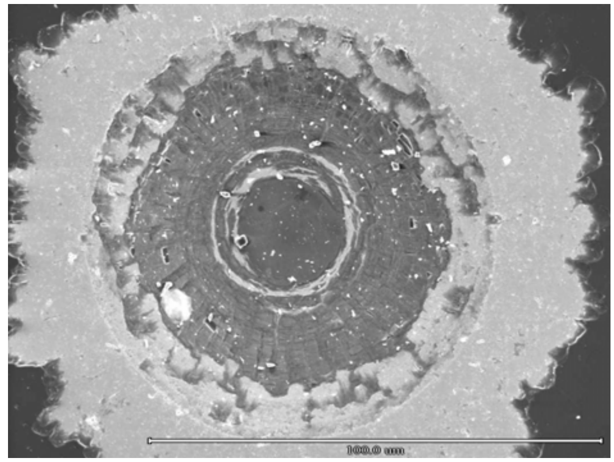


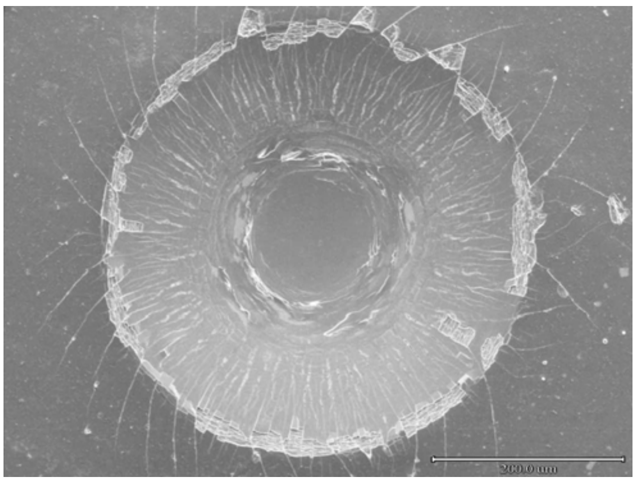
Figure 4: Results of the VDI-3198 Indent Test (Scanning electron microscope, 200X magnification).



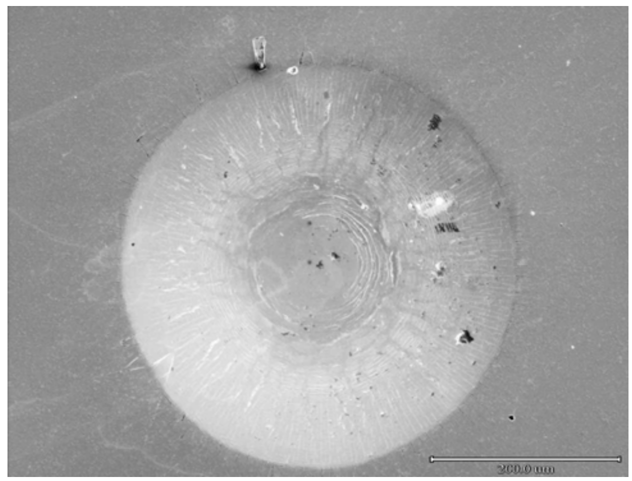
A: Industrial Hard Chrome



B: Diamondlike Carbon (DLC – PACVD)



C: PVD Titanium Nitride Hardcoating



D: IBED Titanium Nitride Hardcoating

Figure 5: Wear rate of various wear-resistant coatings measured by the TaberAbraser test (AMS 2438A). Wear rates are measured as the thickness of the coating removed per 10,000 revolutions of the abrasive wheel (microns per 10,000 revolutions).