COATINGS TECHNOLOGY: A REVIEWING AND COMPARATIVE STUDY OF THE COATINGS TECHNOLOGY AND HOW IT CAN BE USED TO OPTIMIZE PRODUCT DESIGN

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Abstract

It is quite common in the engineering applications that mechanical parts have to successfully withstand a combination of mechanical and chemical loads and serve different purposes. Thus, the need of multi-functional materials arises. This need can be, to some extent, satisfied by coatings. Coatings have the capacity to prevent or decrease the rhythm of the chemical and physical interaction between the substrate and the environment. This way the mechanical, the chemical and the physical properties of the material's surface can be altered. Consequently, coatings can, for example, provide resistance to corrosion, oxidation or fatigue, but also ensure electrical insulation. Thus, with the right use of coatings, the engineer can create parts of high efficiency and also influence the object's Life Cycle. This article, at first, attempts to make a review of the coating technology field, regarding the known techniques, the materials used, their properties and their common applications. Moreover, it includes comparative tables and diagrams that present the ranking of different coatings, concerning each property. The objective is the reader to familiarize with the use of coatings, to appreciate the benefits that can be gained and therefore include the coatings in the design of new products.

Key words: Coatings technology; review; comparative study; design optimization.

Resumen

Es bastante común en aplicaciones de ingeniería que las piezas mecánicas tengan que aguantar a una combinación de cargas mecánicas y químicas. De este modo, se presenta la necesidad de materiales multi-funcionales. Esta necesidad puede ser, hasta cierto punto, satisfecha por los recubrimientos. Los recubrimientos tiene la capacidad de prevenir o disminuir el ritmo de la interacción química y física entre el substrato y el ambiente. Por consiguiente, las propiedades mecánicas, químicas y físicas de la superficie del material se pueden alterar. De este modo, los recubrimientos pueden, por ejemplo, proporcionar resistencia a la corrosión, a la oxidación o a la fatiga, pero también asegurar un aislamiento eléctrico. Así, con un uso apropiado de recubrimientos, el ingeniero puede crear piezas de alta eficiencia y también influenciar en el ciclo de vida del producto. Este artículo, intenta al principio hacer una revisión del campo de la tecnología de los recubrimientos, con respecto a los procesos de deposición, de los materiales usados, de sus características y de los usos comunes. Por otra parte, incluye tablas y diagramas comparativos que presenten el ranking de diversos recubrimientos, por cada propiedad. El objetivo es que el lector se familiarice con el uso de los recubrimientos, apreciar las ventajas que se pueden conseguir y por lo tanto incluir los recubrimientos en el diseño de productos nuevos.

Palabras clave: Tecnología de recubrimientos; revisión; estudio comparativo; optimización del diseño.

1. Introduction

Mechanical parts in engineering applications usually have to endure more than a single load, serve a single purpose or have only one characteristic. Frequently a material has to successfully withstand a combination of mechanical and chemical loads and serve different purposes. Thus, the material of a product is often required to have composite properties which can even be contradictory. For example, gear teeth must be tough to endure mechanical shocks, yet have a low friction surface and withstand erosion. Consequently, the need of multi functional materials arises. The various characteristics required can be divided into two categories, the substrate requirements and the surface requirements.

Among all others, wear, corrosion and friction are the most important factors that engineering parts must confront. The progressive deterioration, due to corrosion and wear, of metallic surfaces in use in major industrial plants ultimately leads to loss of plant efficiency and at worst a shutdown. Economical reports, for the US market, refer almost 300 billion $ annual losses due to corrosion of metals, while scientists support that 40% of the cost could be avoided by proper corrosion prevention methods [1]. Similar are the economical losses due to wear. Recognition of the high cost to industry from wear and corrosion lies behind the continuing development of surface engineering. An important percentage of the surface engineering is occupied by the coatings.

Coatings are applied on to the substrate material by various methods. The choice of the appropriate procedure is based upon the many factors, like the substrate material, part's shape, production size etc. The knowledge of the subject is a necessary tool for the mechanical engineer who is called to design a new product, bearing in mind the demands of an increasing, competitive and expanding market.

The present article attempts to make a brief review of the coating technology field, regarding the known application procedures and the materials used. Furthermore, it includes comparative tables and diagrams that present the ranking of different coatings, concerning each property. Finally, it indicates the common and the possible applications of every coating type. The objective is the reader to obtain a more comprehensive image of the coating technology; thus to familiarize with their use, appreciate the benefits that can be gained and therefore include them in the design of new products.

2. Coatings technology

The compositional requirement of the material necessary to provide adequate strength in a component are usually different from those that provide wear or corrosion resistance, so a composite product consisting of a structural material with protected exposed surfaces naturally comes to mind.

A coating is considered to be a thin layer of a material which is deposited over the surface of another material in order to prevent or decrease the rhythm of the chemical and physical interaction between the substrate and the environment.

Resuming in a few lines the attributes of coatings, it can be said that a coating can provide corrosion and oxidation resistance. Increase the surface hardness and therefore, provide wear resistance. Decrease the friction coefficient and generally improve the mechanical properties of the part. Provide thermal and electrical insulation. Change the optical properties of the surface. Prevent the diffusion of elements from and towards the environment and moreover protect from microbes.

With the right use of coatings, an engineer can create parts of high efficiency. From an engineering point of view, an object is not judged only by its service characteristics, but also from its Life Cycle Analysis (LCA). With the use of coatings, the engineer can choose a

simple material as a base to fabricate a mechanical part and then coat it with a different and better material to meet the service criteria. The profits of that are remarkable and actually the invention of high technology coatings opened new paths in fabrication design. Thus, by using coatings the engineer can accomplish to:

- Use of simpler base material which:
  I. Diminish the cost of purchase of the material
  II. Diminish the tool wear while forming the base
  III. Diminish the lubricants used in forming
  IV. Diminish the energy used in forming
  V. Diminish the time of forming, so increase the productivity
  VI. Achieve high dimensional accuracy
- Diminish friction during service, so gain energy resources
- Diminish wear and corrosion of the part, during service, thus increase service life
- Create parts, which without the coatings would be impossible
- Create parts of complex shape
- Use of non metal materials as a base material

These are some of the characteristics of coatings and how they can be exploited. Yet coatings have various uses and that can be realized by looking closer to objects. Coatings can be found in many applications from every day things like refreshment tins, to high technology parts like semi conductors or aerospace parts.

Due the extensive volume that a detailed description would require, only a brief and indicative report of the coatings' properties and characteristics can be made, which is resumed in Table1. [1-20]

Coating type	Deposition technique	Materials used	Main characteristic
Electro deposition	Vat Plating Selective Plating Electro less deposition	Coating: Zn, Cr, Ni, Ni-P, Cu, Fe, Co, Pb Substrate: most metals	Corrosion and oxidation resist.
Vapor Deposition	Physical VD Vacuum Evaporation Gas Scattering Sputter coating Ion implantation	Coating: AL, TiN, N, Oxides, Carbides, Al2Cr, MoS2, MCrAlY Substrate: Most metals but mainly steels	Corrosion resist. Wear resist. Hardness Low friction Thermal & electrical insulation

	Chemical VD CVD PACVD	Coating: TiC, TiN, SiC, Al2O3, Diamond Substrate: Steels	
Diffusion	Pack Cementation Diffusion Heat Treatment Thermo Reactive diffusion coatings	Coating: Al2O3, Si2O, Cr2O3, N, C, B, Substrate: Steels, Super alloys, Refractory metals	Excellent adhesion High resistance to wear and oxidation. High hardness
Conversion	Chromate Anodizing Hard Anodizing Oxidation treatm.	Coating: Substrate's oxide Substrate: Zn, Aluminium alloys, High speed steels	Corrosion resist. Electrical insulation, Improve lubricity
Dip and Barrier	Continuous Hot Dip Batch Hot Dip Continuous Electro deposition Babbiting Phosphate Porcelain enameling	Coating: Zn, Al-Si, Al-Zn, Pb-Cn, Zn-Cr Substrate: Iron, Low carbon steel, Cold/hot rolled steel, Aluminium alloys	Oxidation and corrosion resist. Improve lubricity
Weld	Arc processes Other techniques: Powder welding Laser Cladding Resistance welding Friction Surfacing	Coating: Wide range of metal alloys Substrate: Steels	Wear resist. Great adhesion High hardness Thick layers

Thermal Spray	Low Energy proces.	Coating: Zn, Al, Substrate: Steel & Aluminium alloys	Corrosion resist.
	High Energy proces.	Coating: Ceramic, carbibes, high alloys Substrate: Steels	Wear resist. High adhesion
Ceramics	Pack cementation, Flame spraying, Electrophoresis, Vapor deposition	Coating: oxides, carbides, silicides, borides Substrate: Steels	Wear & oxidation resist. Thermal & electrical insulation Prevent diffusion
Paint	Spraying Dip painting Flow coating Powder coatings Electrocoating etc.	Coating: Oils, polymers, resins etc. Substrate: Almost every material	Oxidation resist. Aesthetics
Polymers	Flame spraying Fluidised Bed Electrostatic spraying	Coating: thermoplastics and thermosettings. PE-HD, PP, PVC, PS,PET, PU, VF, PC, Epoxy resins Substrate: Metals, Plastics etc.	Corrosion resist. Surface protection Insulation Passivity

Table1. Characterization of coatings

3. Comparison and applications

However, every coating can not provide protection against all chemical or mechanical loads. Even if the primary use of two coatings might be similar, like oxidation protection, it does not mean that they can provide this protection under the same loads. Each coating has its own properties, which can change radically by changing the process details, like temperature, or by changing the materials used. On the other hand, a material can have different chemical

and mechanical properties, depending on the coating method used to deposit it. Therefore, before the engineer makes his selection, it is essential to conduct a close study of the coatings technology [1-6],[21-27]. In order to provide a clearer image about the ranking of the different coating types, we have created diagrams concerning several properties:

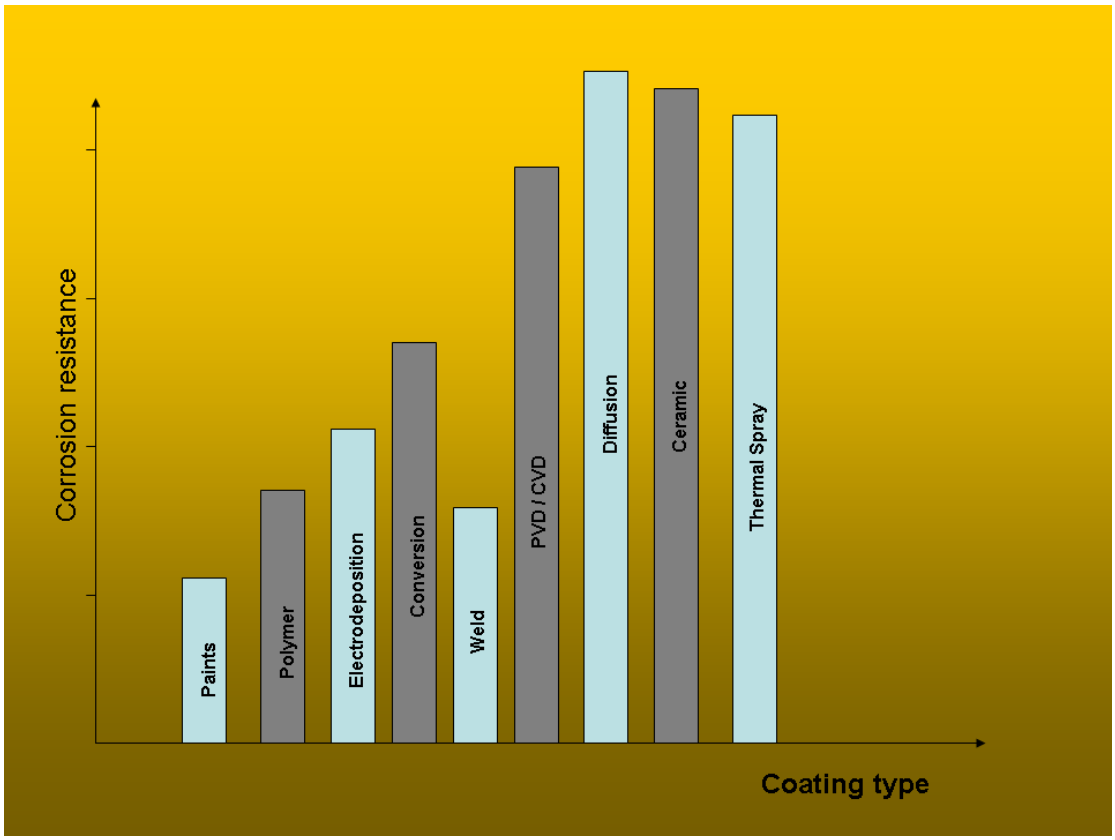

Image1. Corrosion resistance of various coatings

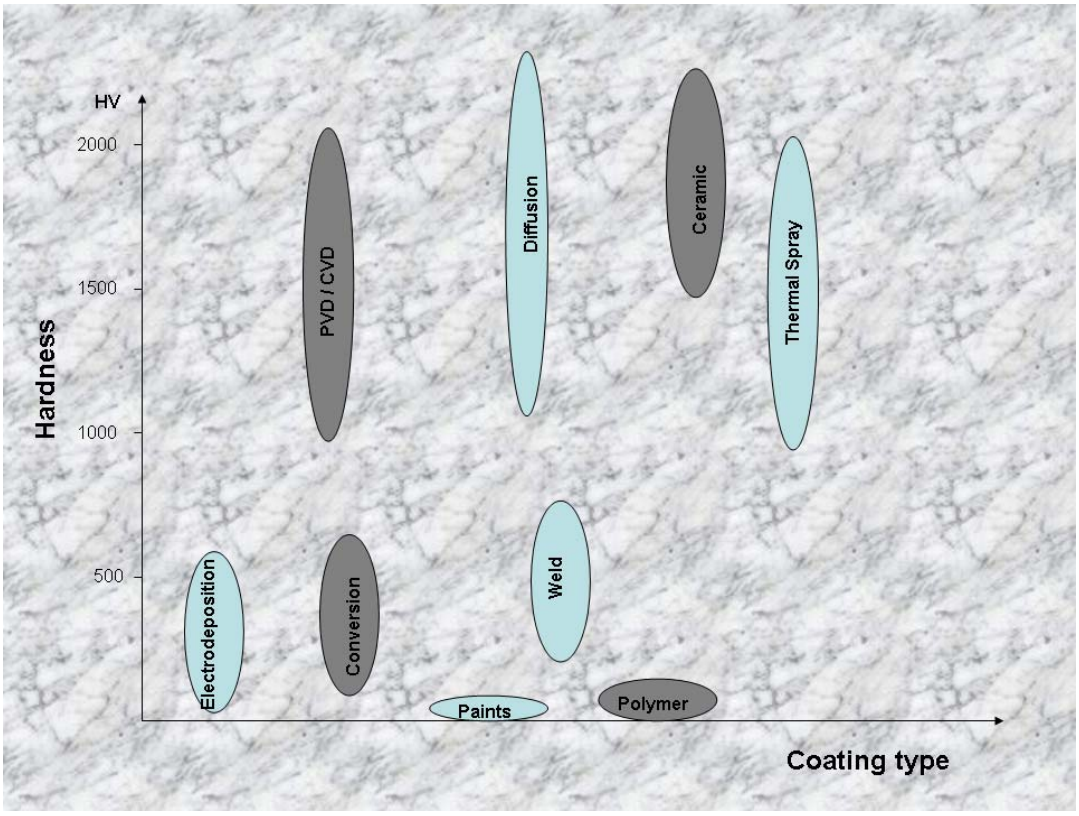

Image1. Surface hardness of various coatings

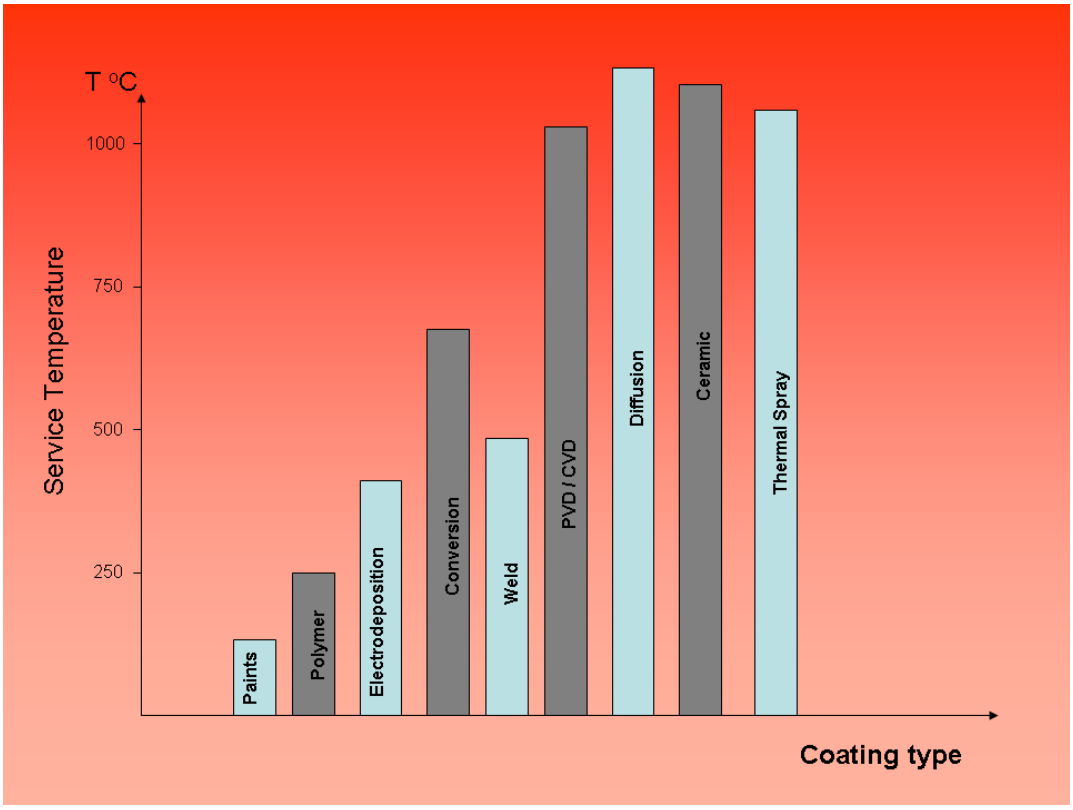

Image1. Service temperature of various coatings

Despite that different types of coatings, exhibit some common properties, they should not be considered as similar. Every coating is a different and separate case. Therefore, every coating is used for specific purposes, under specific service conditions. The following table, summarizes some of the common applications of each coating type. The purpose of the current table is not to indicate the appropriate uses of each coating; but to illustrate the type of application so that the reader can realize the possible uses.

Coating Type	Applications
Electro deposition	Corrosion protection in the heavy industry, Hydraulic equipment, Cutting tools, Piston rings, Electroforming, Water pumps, Heat exchangers, Automotive braking systems, Printing rollers, Overlay coatings of plain bearings or shafts, Surface lubricant in metal working, Stop-off for selective case hardening / for selective nitriding of steels
Vapor Deposition	PVD: Bearings, lenses, Aircraft parts, Semiconductors, Diffusion barriers, Forming tools CVD: Dies, Tools, Gear components, Kneading components, Shafts, Bearings, Nozzles, Turbine blades, Valve parts, Radiation sensors, Nuclear waste containers, Thermo wells, Grinding wheels
Diffusion	Dies, Forming tools, Turbine blades, Shafts, Biomechanics
Conversion	Aero spatial & Aero motive parts, Coil and extraction industry, Heat exchangers, Containers, Marine parts, Computer chip hats, Trays, parts; landing gears, wheel pistons, Canopy tracks
Dip and Barrier	Structural steel, Steel towers, Bridge steel parts, Marine parts, Automotive industry, Mechanical parts like fasteners, screws etc., Nails, Wires, Fences, Utility wires, Hydraulic lines, Roofing, Doors, Fuel tanks, Pipes, Plain bearings
Weld	Shear blades, Dies, Hot work tools, Reconditioning of worn shafts, hard facing of cutting edges, and overlay of slide valve plates, disc brakes and other, Coating cylindrical surfaces as nozzles or flanges, for wear protection, Punches, Industrial gear teeth, Mill rolls, Crane wheels, Pulverisers
Thermal Spray	Shafts, Bearings, Aircraft engines, Prosthetics in biomechanics, Valves, Pumps, Cutting tools, Hydraulic rams
Ceramics	Forming tools, Heat treatment equipment, Nuclear power plan parts

Paint	Everywhere
Polymers	Food industry for packaging, Chemical industry for storage tanks or processing equipment, Automotive industry for corrosion protection and decoration of the exterior parts, Bicycle frames, Electric industry for semi conducting applications

Table1. Common applications of various coatings

Image4. Camshafts; Typical diffusion coating application

Image5. Knee implants; Typical thermal spray coating application

Image6. Roofing; Typical galvanized steel application

Image7. Carabiners; Typical conversion coating application

4. Conclusions

Coatings occupy a large chapter of the engineering field. As a process, it involves the knowledge and use of several sciences, like mechanics of materials, physics and chemistry. As a designing tool, it can provide the engineer with an accessory of numerous chemical and mechanical properties, thus allowing him to alter and optimize the design of various parts and their mechanisms.

Nevertheless, the choice of the right coating type and its deposition parameters is a process that undertakes a lot of time and experience. The current variety of different coatings and the materials or alloys that can be used, results in an infinite combination of materials and properties.

The basic points that should be noted are:

- Different types of coatings, exhibit some common properties, but they should not be considered as identical. Every coating is a different and separate case.
- It is must be emphasized that a there is no coating that can provide ultimate protection or improvement to every property, mechanical or chemical, of the material.
- When protection is required under aggressive environments or intense mechanical conditions, the adequate coatings are usually of high technology and impose constrains over the substrate choice.
- Simple and therefore cheap coatings usually provide protection against corrosion and oxidation in mild environmental conditions.
- Compatibility and adhesion between the substrate and the coating material, combined with the selected technique, is of great importance. The process details, like temperature, implementation time and chemical catalysts, can affect negatively the performance of the coating, thus constraining the possible material choices.
- There is an essential differentiation between the techniques appropriate for mass production and those for small production, although there are cases where the technique can be adjusted to the production type.
- Not every technique can be used for coating any object shape. These two should be compatible. Therefore, the design has to be adapted to the selected coating technique and vice versa.
- It is of great importance that the service conditions and the desired properties are carefully assessed.

Nevertheless, the benefits that can be gained by the use of coatings compensate the dedicated time. With the use of coatings, the engineer can create parts with different substrate and surface properties. The profits of that are tremendous and actually the invention of high technology coatings opened new paths in fabrication design. Therefore, it is the authors' opinion that engineers should, by all means, increase the use of coatings in their designs.

References

[1]. Grainer St. and Blunt J., "*Engineering Coatings-Design and applications*", Abington Publishing, Cambridge, 1998.

[2]. Davis J.R, "*Surface Engineering for corrosion and wear resistance*", ASM International, Inc. 2001.

[3]. ASM, "*Surface engineering, Handbook V.5*", ASM International, 1994

[4]. Brock Th., "*European Coatings Handbook*", Curt R. Vincentz, Hannover, 2000

[5]. ASM, "*Surface cleaning. Finishing .Coating. Metals Handbook V.5*", ASM International, 1982

[6]. Osswald T.A., "*Materials Science of polymers for Engineers*", Hanser & Gardner Publications, Munich, 1996

[7]. Jindal P.C. et al., "Performance of PVD TiN, TiCN, and TiAlN coated cemented carbide tools in turning", *International Journal of Refractory Metals & Hard Materials*, Vol.17, 1999, pp.163±170

[8]. Hirvonen J.-P. et al., "Present progress in the development of low friction coatings", *Surface and Coatings Technology,* Vol. 80, 1996, pp.139-150

[9]. Pal Dey S. and Deevi S.C., “Single layer and multilayer wear resistant coatings of (Ti,Al)N: a review”, *Materials Science and Engineering*, Vol. A342 ,2003, pp.58- 79

[10]. Mitterer C. et al., “Structure and properties of decorative rare-earth hexaboride coatings”, *Surface and Coatings Technology*, Vol. 86-87, 1996, pp.715-721

[11]. Choy K.L., “Chemical vapour deposition of coatings”, *Progress in Materials Science*, Vol. 48, 2003, pp.57-170

[12]. Heinze M., “Wear resistance of hard coatings in plastics processing”, *Surface and Coatings Technology*, Vol.105, 1998, pp.38–44

[13]. Martinu L. and Poitras D., “Plasma deposition of optical films and coatings: A review”, Journal of Vacuum. Science. Technology, Vol.A 18(6), Nov/Dec 2000

[14]. Mattox D.M., “Surface effects on the growth, adhesion and properties of reactively deposited hard coatings”, *Surface and Coatings Technology*, Vol. 81, l996, pp.8-16

[15]. Vahlasa C. et al., “Principles and applications of CVD powder technology”, *Materials Science and Engineering,* Vol.R 53, 2006, pp. 1–72

[16]. Jyh-Wei Lee, Jenq-Gong Duh, “Evaluation of microstructures and mechanical properties of chromized steels with different carbon contents”, *Surface and Coatings Technology*, Vol. 177 –178, 2004, pp. 525–531,

[17]. Sang Yul Lee et al., “Mechanical properties of duplex layer formed on AISI 403 stainless steel by chromizing and boronizing treatment”, *Surface and Coatings Technology* Vol. 177 –178, 2004, pp.178-184

[18]. Katsamas A.I. and Haidemenopoulos G.N., “Laser-beam carburizing of low-alloy steels”, *Surface and Coatings Technology*, Vol. 139, 2001, pp.183-191

[19]. Marder A.R., “The metallurgy of zinc-coated steel”, *Progress in Materials Science,* Vol.45, 2000, pp.191-271

[20]. Barletta M. et al, “Electrostatic spray deposition (ESD) of ‘self organizing’ TiO_2-epoxy powder paints: Experimental analysis and numerical modelling”, *Surface and Coatings Technology*, Vol. 201, 2006, pp.3212–3228

[21]. Hermann A. J., “PVD and ECD-competition, alternative or combination?”, *Surface and Coatings Technology,* Vol. 112 ,1999, pp.210–216

[22]. Quinto D. T., “Technology Perspective on CVD and PVD Coated Metal-Cutting Tools”, *lnt. J. of Refractory Metals & Hard Materials*, Vol.14, 1996, pp.7-20

[23]. Navinsek B. et al., “PVD coatings as an environmentally clean alternative to electroplating and electroless processes”, *Surface and Coatings Technology,* Vol.116–119, 1999, pp.476–487

[24]. Coldwella H.L. et al., “The use of soft lubricating coatings when dry drilling BS L168 aluminium alloy”, *Surface and Coatings Technology*, Vol.177 –178 ,2004, pp.716–726

[25]. Pochet L. et al., “CVD coatings: from cutting tools to aerospace applications and its future potential”, *Surface and Coatings Technology*, Vol. 94-95, 1997, pp. 70-75

[26]. Barletta M., “Electrostatic fluidized bed (EFB) coating of heat sensitive and electrical insulating substrates with low-curing thermoset epoxy-polyester (EP) powders”, *Progress in Organic Coatings*, Vol. 56, 2006, 185–198

[27]. Cao X.Q. et al., “Ceramic materials for thermal barrier coatings”, *Journal of the European Ceramic Society,* Vol. 24, 2004, pp.1–10

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